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THE NOISE OF ELECTRONIC VALVES AT VERY HIGH FREQUENCIES

I. THE DIODE

by G. DIEMER and K. S. KNOL. 621.396.822:621.396.645.029.6

Noise of radio and television receivers, in so far as it is produced in the receiver itself, is caused by a number of rather complicated phenomena. These phenomena can nevertheless be investigated fairly well theoretically at wavelengths that are not too small. However, at wavelengths within the decimetric and particularly centimetric ranges the noise problem becomes more difficult. The transit times of the electrons passing through electronic valves are then no longer small compared with the oscillation of the alternating electric field, so the waveform of the individual current pulses plays a part. This article explains the complications this leads to in the analysis of the noise phenomenon of a diode. In another article to be published later, noise phenomena in triodes will be investigated at very short wavelengths. It will be shown then how noise is affected by the nature of the circuit in which the valve is employed.

The term "noise", originally derived from acoustics, is used in electrical engineering in a very general sense. Here it is used to denote random fluctuations, for instance of currents and voltages. Such fluctuations may be of thermal origin — thermionic noise — or they may be connected with the corpuscular structure of electricity. In electronic valves the number of electrons passing through a certain cross section of a valve per unit time is subject to variations, and this causes fluctuations in the current flowing through the output circuit.

The causes of the noise which occurs, for instance in radio and television receivers and amplifiers at high frequencies (metric and decimetric waves), have been dealt with in previous issues of this journal [1]). Since then, however, the frequency range that can be used for practical purposes has been extended to cover centimetric waves, and this has given rise to all sorts of specific problems, connected with noise. It is these problems that will be treated in the present article. Following upon a general introduction, attention will be directed particularly to the noise of a diode. Another article is to follow, dealing with the noise of a triode and the manner in which noise is affected by the circuit in which the valve is working.

The causes of noise in radio and television receivers can be classified under three headings: those outside the receiver (aerial noise), those contained in the electronic valves of the receiver (electronic noise) and those in the other parts of the receiver (network or Johnson noise). Since our intention is to investigate the electronic noise in particular, the other two categories will be reviewed only briefly. Further information about them can be found in the literature referred to in footnote [1]).

Aerial noise and network noise

Aerial noise

The primary contribution to aerial noise is made by electrical apparatus in the vicinity of the receiver. The ignition mechanisms of motor vehicles, gas-discharge lamps, electric motors and suchlike

[1]) M. Ziegler, Philips techn. Rev. 2, 136-141, 1937; 2, 329-333, 1937, and 3, 189-196, 1938; C. J. Bakker, Philips techn. Rev. 6, 129-138, 1941; M. J. O. Strutt and A. van der Ziel, Philips techn. Rev. 6, 178-185, 1941.

are sources of noise known to many of us from experience. Electric discharges (sparking, for instance) always result in electromagnetic radiation over a wide frequency range, and it is this radiation that manifests itself as noise. It can often be counteracted fairly well at its source and is often called man-made interference, to distinguish it from other phenomena to be dealt with below.

Electric discharges also take place in the atmosphere, namely the discharges of electric storms (lightning). Electro-magnetic radiation with a wavelength greater than about 20 metres is reflected back to earth by the ionosphere, so that atmospheric noise in this wave range may become noticeable at very great distances from its source. The electric storms which occur so frequently in the tropics can thus cause atmospheric noise over the whole of the earth. On wavelengths less than 10 to 20 metres, however, the effect of atmospheric noise is less noticeable.

There is also electro-magnetic radiation of a cosmic origin (galactic noise). In recent years such radiation has proved of great importance in astronomy, but here we are concerned solely with the fact that it acts as a source of noise in receivers. Since the ionosphere transmits only radiation with a wavelength less than about 20 metres, cosmic noise is troublesome on the short waves only. It is strongest on the wavelengths between 1 and 10 metres, where cosmic noise is comparable to atmospheric noise and the noise of the receiver itself. In the construction of receivers for wavelengths in this wave range, therefore, it serves little purpose to pay very much attention to receiver noise. On the ultra short waves (below 1 metre) the intensity of cosmic radiation is so small that little trouble is experienced from it; in this region, therefore, it is important to restrict receiver noise as far as possible.

Network noise

From thermodynamic considerations it can be deduced that every resistance, R, occurring in a circuit acts as a source of noise. It is equivalent to a current generator with parallel conductance $1/R$, producing a fluctuating short-circuit current i. The mean square value of i in the frequency range between f and $f + \Delta f$ is given by:

$$\overline{i^2} = \frac{4kT}{R}\,\Delta f, \quad \ldots\ldots \quad (1a)$$

where T represents the absolute temperature of the resistor and k is Boltzmann's constant. This expression is not frequency dependent. The resistor may also be regarded as a noise-voltage generator with internal resistance R, yielding a fluctuating e.m.f. u. The mean square value of u in the frequency range between f and $f + f\,\Delta f$ is given by

$$\overline{u^2} = 4\,kTR\Delta f. \quad \ldots\ldots \quad (1b)$$

The resistor is, of course, coupled to the rest of the circuit, which must be regarded as a load on the noise generator. Assuming for a moment that the resistor and the rest of the circuit are at the same temperature, there is just as much noise power passing from the resistor to the circuit as in the opposite direction. This noise power is a maximum when the internal resistance of the circuit is equal to R (optimum matching). As a time average the noise power in a frequency range Δf is then equal to

$$p_{\max} = kT\,\Delta f. \quad \ldots\ldots \quad (2)$$

If the temperature of the resistor differs from that of the circuit, which is, let us say, at room temperature T_0, then the thermodynamic equilibrium on which the above considerations are based is broken; there is no longer the same amount of power passing in both directions. With optimum matching, however, the noise power produced by the resistor is still equal to the value given by formula (2). The ratio of T to T_0 is called the noise factor F of the resistor. The factor F is a ratio of two powers and is often expressed in decibels, being called then the noise figure (N). It appears that the conception of a noise factor can easily be extended to the case where a non-thermal source of noise is present.

Different parts of the noise-producing resistor (or, more generally, the noise-producing network) may have different temperature. Then a certain average T^* of the temperatures occurring in the network, the equivalent noise temperature, can be defined such that

$$p_{\max} = kT^*\Delta f. \quad \ldots\ldots \quad (3)$$

F is then given by T^*/T_0.

Deviations from thermodynamic equilibrium may also arise in another way, when the circuit contains sources of macroscopic voltages giving rise to macroscopic currents in the resistors [2]). In metallic resistors, even when the current is large, there is only a very slight disturbance of the equilibrium, so the noise does not change (the drift velocity of the electrons is small compared with their thermic velocities). In semi-conductors, carbon resistors or

[2]) By macroscopic quantities are meant those quantities which are not subject to random fluctuations, such as, for instance, ideal battery and signal voltages. These quantities will be indicated in capital letters, to distinguish them from noise quantities (which might also be called microscopic quantities) written in small letters.

contact resistors, however, a macroscopic current may cause a considerable increase in the noise (apart from any increase due to a rise in temperature). This noise appears to be frequency dependent, being greatest usually at low frequencies.

Electronic noise at frequencies up to 10^7 c/s

A thermodynamical approach has been used, so far, in describing the causes of noise in electronic valves. It is equally possible, however, to describe them in terms of the corpuscular structure of an electronic current. There is one type of valve, that having a double cathode [3]), in which the electrons are in thermodynamic equilibrium with the surroundings; the same result is reached in this case, whichever method of reasoning is followed. In other types of electronic valves, however, great deviations from thermodynamic equilibrium commonly occur, so in this article the second method of reasoning will be followed, except where the laws of thermodynamic equilibrium are obviously applicable.

The problem of noise in electronic valves is already rather a complicated one, but for very high frequencies (10^9-10^{11} c/s) it becomes still more difficult, since the transit times of the electrons are comparable to the cycle of the alternating field. We shall therefore consider first electronic noise at medium frequencies, in the range of the decametric waves. This has already been discussed at length in the articles quoted in footnote [1]), so here a summary will be given, supplemented by results of more recent investigations in this field.

Shot effect

The number of electrons passing through a certain cross section of a valve per unit is subjected to fluctuations owing to statistical fluctuations in the number of electrons emitted by the cathode per unit time. It can be proved that the noise of a saturated diode — that is a diode in which the anode is at such a high potential that all electrons leaving the cathode are attracted to the anode — is caused entirely by shot effect. The fluctuations in anode current are expressed, as before, by the mean square value of the amplitude of the noise current in the frequency range between the frequencies f and $f + \Delta f$. They are given by:

$$\overline{i^2} = 2eI_a\Delta f, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where I_a stands for the anode direct current and e is the absolute value of the electron charge. This formula for the noise due to shot effect applies for all valves, subject only to the condition that the electrons move towards the anode independently of each other, as they do, for instance, in the exponential range of a diode. If, there is space charge, formula (4) no longer holds.

Saturated diodes are often used as noise standards. For not too high frequencies the internal parallel conductance is zero ($\mathrm{d}I_a/\mathrm{d}V_a = 0$, the characteristic of saturation), so that the diode is an ideal current generator. For frequencies at which the finite transit time of the electrons begins to play a part, formula (4) is no longer correct, for the noise then decreases in intensity. A diode which serves as a noise standard as far as the decimetric-wave range is the Philips type 10 M diode.

Effect of space charge (noise suppression)

Epstein has shown that the potential in a diode at the average anode voltage varies in the manner represented in *fig. 1*. There is a minimum in the

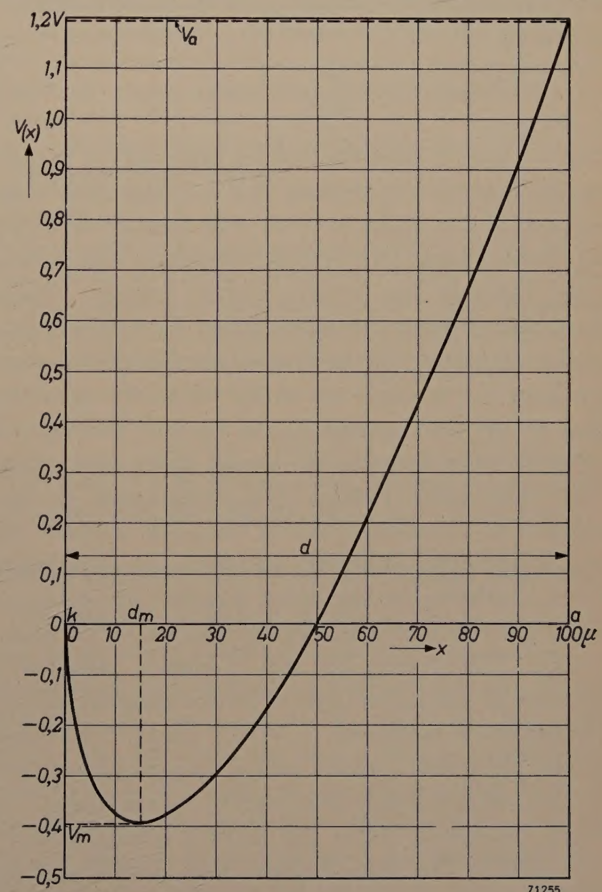

Fig. 1. Potential distribution in a diode with space charge, for a practical case. The potential $V(x)$ is plotted as a function of the distance x from the cathode k (imagined as being at a potential 0); d is the distance between the electrodes, V_a the anode voltage. At a distance d_m from the cathode is a minimum in the potential curve, with depth V_m. The potential minimum is the most difficult part of the valve for the electrons to pass through (owing to their negative charge).

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[3]) D. K. C. MacDonald, Proc Roy. Soc. A **195**, 225-230, 1948; K. S. Knol and G. Diemer, Philips Res. Reports **5**, 131-152, 1950.

potential curve near the cathode (at a distance d_m), this being due to the space charge formed by all the electrons which at a certain moment are present between the cathode and the anode. This potential plot follows from theoretical considerations [4]). Experimentally it can be checked only indirectly, owing to various disturbing effects making the results of the experiment rather uncertain (variations in the work function across the electrode surfaces, secondary anode emission and suchlike). It is not, therefore, to be expected that the following considerations will show any exact numerical agreement with what is found in practice. The depth of the potential minimum depends upon several factors, amongst them the anode voltage and the cathode temperature; if the anode voltage is very high or the cathode temperature very low, there is no minimum.

The electrons do not all leave the cathode at the same velocity. The average number of electrons $\overline{N}(v_x)\mathrm{d}v_x$ having a forward velocity component between v_x and $v_x + \mathrm{d}v_x$ is given by the distribution function:

$$\overline{N}(v_x)\mathrm{d}v_x = \frac{I_s m}{ekT} e^{\frac{mv_x^2}{2kT}} v_x \mathrm{d}v_x, \quad \ldots \quad (5)$$

where k and T have the known meaning, m stands for the mass of the electron and I_s is the saturation current of the cathode. Only the fastest electrons are able to pass the potential minimum and contribute towards the anode direct current. $N(v_x)$ fluctuates around the value given by formula (5). If the amplitude of the fluctuations in the current reaching the anode were to be relatively equal to that of the fluctuations in the current leaving the cathode, then formula (4) would apply also when there was space charge. The fluctuations in the number of electrons passing from the cathode to the anode are, however, relatively smaller than those occurring in the total number of electrons leaving the cathode, so the noise is proportionately weaker. The reason for this is that a temporary increase of the number of electrons emitted makes the potential minimum so much deeper that some of the electrons — those whose velocities lie within certain narrow limits (see below) — are unable to reach the anode. Thus the noise is partially suppressed by the space charge. This is expressed by the formula:

$$\overline{i^2} = \Gamma^2 2eI_a\Delta f, \quad \ldots \ldots \quad (6)$$

where Γ represents the noise-suppression factor: $\Gamma < 1$.

[4]) P. H. J. A. Kleijnen, Philips Res. Rep. 1, 81-96, 1946; A. van der Ziel, Philips Res. Rep. 1, 97-118, 1946.

For low frequencies it is possible to calculate the value of this factor Γ [5]). In *fig. 2* both calculated and experimental values of Γ^2 are given as functions of the anode voltage. The noise has been measured on a triode connected as diode and to be regarded as a diode with a very low secondary emission.

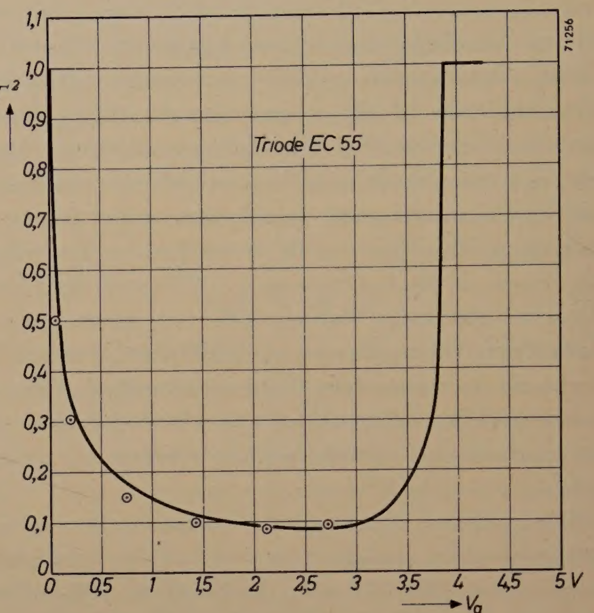

Fig. 2. The square of the noise-suppression factor Γ at the frequency $6 \cdot 10^6$ c/s as a function of the anode voltage V_a. This diagram applies for the triode EC 55 connected as a diode. The curve represents the theoretical trend, while the small circles are the values found experimentally.

Reflection noise

Electrons reaching the anode may be reflected back by the surface of the anode and they may also release secondary electrons from the anode. The reflected electrons are the fastest, possibly penetrating into the region of the potential minimum and thus increasing its depth; the secondary electrons are much slower and as a rule have little effect. This effect of the reflected electrons reduces the anode direct current but increases the noise intensity. The number of returning electrons fluctuates in time. Denoting the average reflected-electron current passing from the anode to the potential minimum by I_r and the electron current reaching the anode by I_a, then:

$$I_r = rI_a,$$

where r is the reflection coefficient. According to (4) the fluctuations in I_r will be given by:

$$\overline{i_r^2} = 2eI_r\Delta f = 2erI_a\Delta f.$$

For the sake of simplicity it will be supposed that all the reflected electrons reach the cathode. An upper limit may then be found for their effect upon the noise: I_r must be subtracted from I_a and i_r added to i_a. Owing to the deepening of the potential minimum, fluctuations arise in I_a which are practically equal to i_r. At low frequencies these fluctuations are in

[5]) W. Schottky and E. Spenke, Wiss. Veröff. Siemens Werke 16[II], 1-41, 1937; D. O. North, B. J. Thompson and W. A. Harris, R.C.A. Rev. 4, 269-289 and 441-472, 1940.

the same phase as those in I_r, so that the total fluctuations in I_a due to reflected electrons is given by:

$$\overline{(2i_r)^2} = 8er\,I_a \Delta f.$$

The shot effect in the anode current gives rise to the fluctuations expressed by formula (6), so the total noise is given by:

$$\overline{i^2} = \overline{i_a^2} + \overline{(2i_r)^2} = 2eI_a\,(\Gamma^2 + 4r)\,\Delta f \quad . \; . \; . \; . \; . \quad (7)$$

If, for instance, $\Gamma^2 = 0.05$, which is a fairly normal value, an anode reflection coefficient of 1% is already sufficient to double the intensity of the noise, as is illustrated in *fig. 3.*

Secondary-emission noise

A surface specially prepared for the purpose can act as electron multiplier through secondary emission. The number of secondary electrons released by a primary electron varies statistically: for a given surface there is an emission function $\beta(m)$ indicating the chance of a primary electron releasing m secondary electrons. The mean value of m is called the secondary-emission coefficient δ of the surface, δ being given by:

$$\delta = \overline{m} = \Sigma\beta(m)\,m\,.$$

For a good secondary-emitting surface the coefficient δ will be about 5.

Owing to the fluctuations in m, the secondary-emission current I_{sec} generated by a primary current I_{pr} (for the present imagined as being free of fluctuations) will cause noise. According to the rule of probability the spread in the number of secondary electrons per primary electron is given by:

$$\sigma^2_{sec} = \overline{m^2} - (\overline{m})^2 = \varkappa\delta - \delta^2 \,(> 0),$$

where $\varkappa\delta$ is substituted for $\overline{m^2} = [\Sigma\beta(m)\,m^2]$ in order to arrive at an expression that can be conveniently handled.

The mean secondary direct current I_{sec} is equal to δI_{pr}, and from the foregoing it can be deduced that the noise in the secondary direct current is given by:

$$\overline{i^2_{sec}} = 2eI_{pr}\,\delta(\varkappa - \delta)\,\Delta f = 2eI_{sec}\,(\varkappa - \delta)\,\Delta f \quad . \; . \; . \quad (8)$$

If fluctuations occur also in the primary current according to (4), (6) or (7), then these contributions towards $\overline{i^2}$ have to be added to (8).

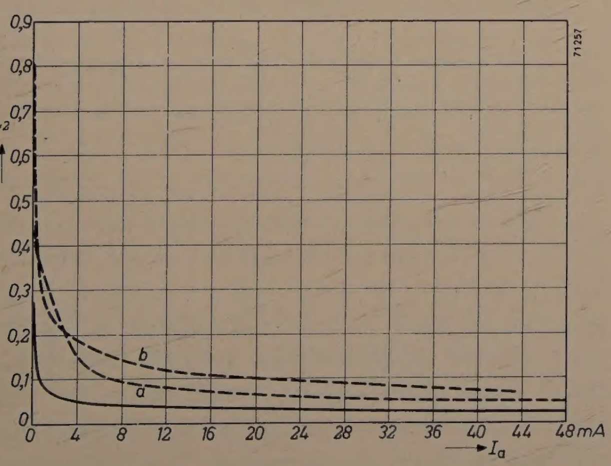

Fig. 3. Influence of the reflectivity of the anode upon the noise of a diode. Fully drawn curve: theoretical value of Γ^2 as a function of the anode current I_a for a reflection coefficient 0. Broken curves: *a* experimental values for an anode covered with fluffy soot (low reflection coefficient), *b* experimental values for a polished nickel anode (higher reflection coefficient).

Flicker effect

At frequencies lower than 10 000 c/s the anode current fluctuations in a diode often exceed the value calculated according to (6). The intensity of this additional noise appears to increase approximately in inverse proportion to the frequency. This additional noise is ascribed to local changes taking place in the cathode surface, which have rather a long characteristic duration [6]).

Ion noise

In some cases ions are emitted by the cathode or produced by the stream of electrons if gas is still present in the valve. If there is a potential minimum these slow ions may greatly influence it owing to the length of time that they remain near it. The result is an increase of the noise at frequencies lower than the reciprocal transit time, i.e. usually at wavelengths greater than a few metres.

Quantum noise

At very high frequencies another type of noise may arise, connected directly with the quantum character of the electromagnetic radiation [7]). In a cavity resonator filled with electromagnetic radiation which is in thermodynamic equilibrium with the surroundings, a number of quanta pass a given cross section every second. This number fluctuates statistically. A radiation quantum in the order of 1.3×10^{-4} eV corresponds to radiation of a wavelength of 1 cm. This means that in a cavity resonator with an alternating field of this wavelength the energy, and thus the velocity of an electron, can change only discontinuously, in steps corresponding to 1.3×10^{-4} eV. It has not yet been possible to detect the noise which must result from this.

Partition noise

In a valve having several electrodes there will be fluctuations in the distribution of electrons among the electrodes. When a certain electrode takes up on an average the proportion p of the total current I then, according to the rule of probability, the fluctuations in the current flowing towards that electrode are given by:

$$\overline{i_p^2} = 2ep(1-p)I\Delta f. \quad . \; . \; . \; . \; . \; . \; . \quad (9)$$

Here again, any fluctuations already present in I have to be added to those given by (9).

Electronic noise of a diode at very high frequencies

As already remarked, in the range of very high frequencies the description of noise phenomena is made very complicated by the fact that the transit times of the electrons in the valve (in the order of 10^{-10} to 10^{-8} sec) are then no longer small compared with the cycle of the alternating field. It can be shown that both the width and the waveform of the current pulses produced by individual electrons passing through the valve then begin to play a part. There is a change in the effect of the causes of noise already mentioned and other causes arise, as will be seen from the following.

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[6]) J. G. van Wijngaarden, Thesis "Vrije Universiteit" Amsterdam, 1951.
[7]) D. K. C. MacDonald and R. Kompfner, Proc. Inst. Radio Engrs **37**, 1424-1426, 1949; **38**, 304, 1950.

Current pulses in an electronic valve

An electron travelling towards the anode causes a current pulse in the anode circuit owing to the induction of charges on the electrodes (cathode and anode). The shape of this pulse (its variation as a function of time) depends upon the kinetic state of the electron. Let us consider, with reference to *fig. 4*, an electron moving between two flat metal

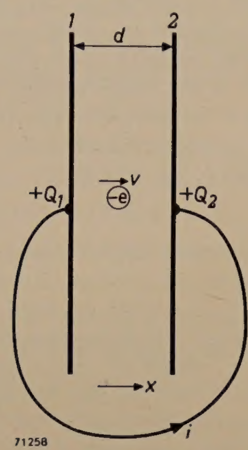

Fig. 4. Illustration of the current induced in the external lead.

plates *1* and *2* kept at the same potential by a conducting connection. The charge induced by the electron on plate *1*, Q_1, and that induced on plate *2*, Q_2, will depend only upon the distance x between the electron and plate *1*, assuming that the plates are so large that fringing effects may be ignored. The charges induced may then be calculated by imagining the charge of the electron, e, as being spread out over a plane parallel to the electrodes. Denoting the distance between the electrodes by d, then:

$$Q_1 = \frac{d-x}{d}\, e,$$

$$Q_2 = \frac{x}{d}\, e\,.$$

Thus the current i flowing in the external circuit is:

$$i = \frac{\mathrm{d}Q_2}{\mathrm{d}t} = \frac{e}{d}\,\frac{\mathrm{d}x}{\mathrm{d}t}\,.$$

The instantaneous value of the current therefore depends only upon the velocity of the electron, and not upon its position. Hence a current will flow in the external circuit even before the electron has reached plate *2*; this is an induced current. In the valve one may speak of a convection current, the instantaneous value of which is related to the position of the electrons: this instantaneous value is equal to the net amount of charge flowing per unit time through a given cross section of the valve. At low frequencies the convection current is equal to the current in the external circuit. At frequencies which are in the order of the reciprocal transit time of the electrons account has to be taken of the induced current, and thus the convection current at any instant is only indirectly related to the current flowing at that instant in the external circuit. The convection current cannot then be determined by measurement.

At low frequencies the current pulse generated in the external circuit by an individual electron can be considered infinitely narrow. *Fig. 5a* shows diagrammatically how the current produced in the external circuit by all the electrons passing through the valve can then be imagined as comprising a series if infinitely narrow pulses (assuming that we have a saturared diode with negligible space charge). A Fourier analysis of such a current shows that all frequencies are equally represented in it (fig. 5*b*). Therefore, at low frequencies the electronic noise of a valve may be regarded as independent of frequency (formula (4)).

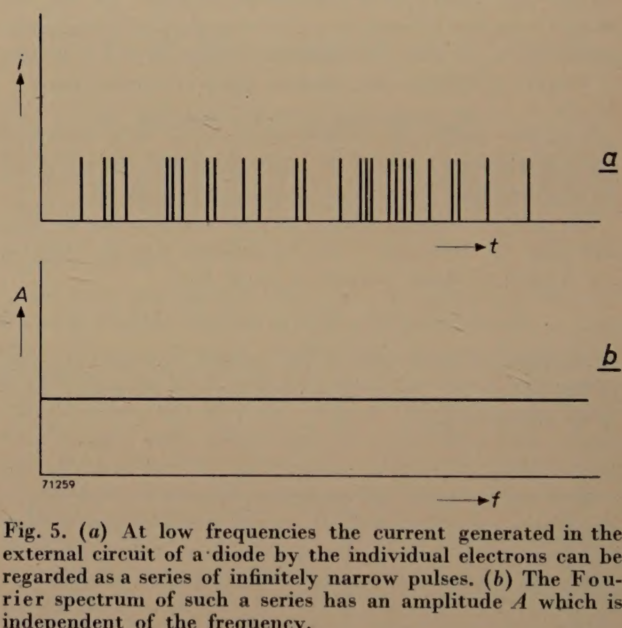

Fig. 5. (*a*) At low frequencies the current generated in the external circuit of a diode by the individual electrons can be regarded as a series of infinitely narrow pulses. (*b*) The Fourier spectrum of such a series has an amplitude A which is independent of the frequency.

At high frequencies it must be taken into account that in reality the current pulses are not infinitely narrow but of finite width and are erratic in shape. A series of such pulses is illustrated in *fig. 6a*. (It should be recognized that actually these pulses follow each other in such rapid succession that they almost entirely overlap, so the illustration is not true to actual conditions.) A Fourier analysis of a pulse of this shape shows that in the spectrum there is an almost constant part extending to frequencies in the order of the reciprocal duration of the pulse, i.e. the reciprocal transit time of the

electron (fig. 6*b*). At higher frequencies the noise caused by the electrons decreases, as already mentioned in the discussion on the saturated diode as a noise standard.

The shape of the current pulses in a diode will now be considered in greater detail.

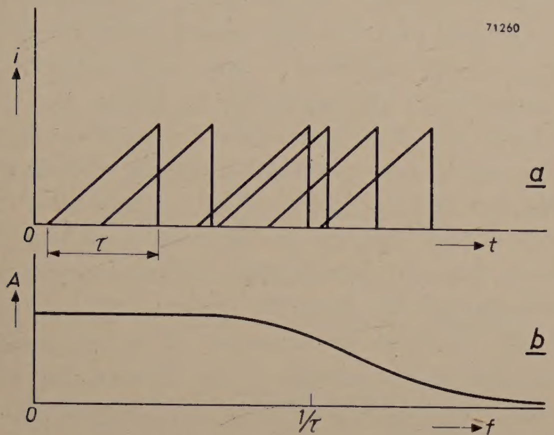

Fig. 6. (*a*) At very high frequencies the individual current pulses in the external circuit of a valve can no longer be treated as infinitely narrow pulses; their width is in the order of the reciprocal transit time τ of the electrons. In this diagram the pulses have been fairly well separated, but actually they follow each other in such a rapid succession as to overlap almost completely. (*b*) The amplitude of the Fourier spectrum of this series of pulses begins to decrease at frequencies in the order of the reciprocal transit time.

Current pulses in a diode at very high frequencies

Again we shall consider the case of a diode with plan-parallel electrodes. It the anode voltage is so high and the emission current so small (low cathode temperature) that the velocity with which they leave the cathode and the space charge may be ignored, the electrons pass from the cathode to the anode with a uniform acceleration. The shape of the current pulse generated by an electron in the short-circuited external circuit is then triangular (*fig. 7a*). If there is space charge, but the resultant potential minimum lies practically on the cathode surface (as may be the case when the anode voltage is still rather high), then to a good approximation the potential in the valve varies, according to Child [8]), as:

$$V(x) \sim x^{4/3}.$$

From this it can be deduced that the velocity of an electron at a moment t after leaving the cathode is given by an expression of the form:

$$v(t) \sim t^2. \quad \dots\dots\dots \quad (10)$$

The shape of the current pulses is then parabolic, as represented in fig. 7*b*. In these figures τ stands for the total transit time of the electron.

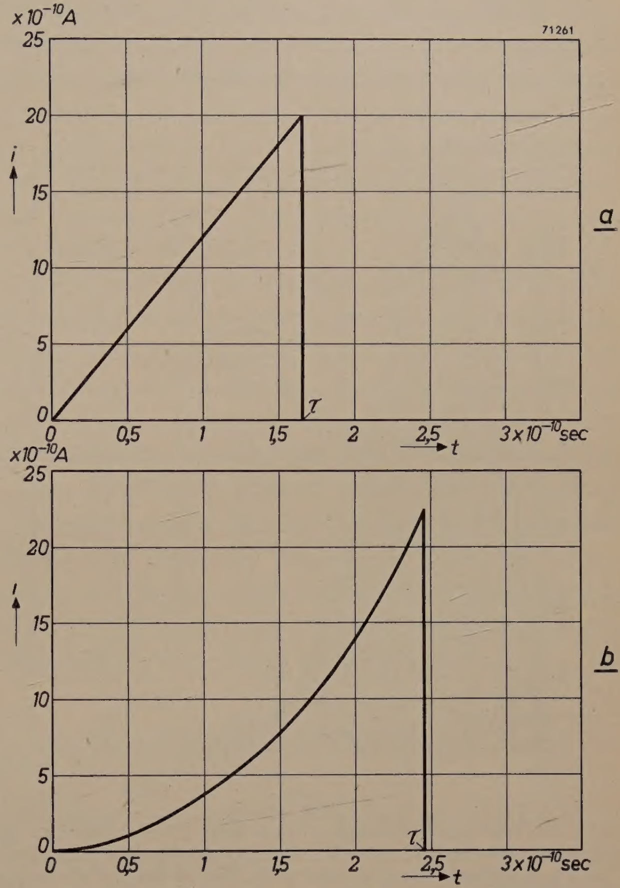

Fig. 7. Shape of the current pulse (variation of the current i as a function of the time t) generated in the external circuit of a flat diode, by an electron passing from cathode to anode: (*a*) for a diode without space charge, (*b*) for a diode answering Child's law (formula (10)); τ stands for the transit time of the electron. This is only a schematic diagram.

If the space charge is so great that the potential minimum no longer lies on the cathode but somewhere between the cathode and the anode, then various shapes of current pulses are possible. There are then three distinct categories of electrons (see *fig. 8*):

1) α-electrons — these are electrons which cannot pass the potential minimum and which therefore return to the cathode. They usually form the major part of all the electrons, so that the number of these α-electrons starting per second can be taken to be practically equal to the total stream of electrons leaving the cathode. They are, in fact, often referred to as total-emission electrons, and the phenomena to which they give rise are called total-emission phenomena. The current pulses of α-electrons are roughly of the shape depicted in *fig. 9a*. After leaving the cathode with a certain initial velocity at the moment $t = 0$, an electron is retarded and at the moment τ_a turned

[8]) D. C. Child, Phys. Rev. **32**, 492-511, 1911; I. Langmuir, Phys. Rev. **2**, 450-486, 1913.

back. It is then accelerated in the reverse direction until it reaches the cathode again at the moment $2\tau_a$. In the vicinity of τ_a part of the slope of the current pulse is less steep, and the closer the electron gets to the potential minimum before turning

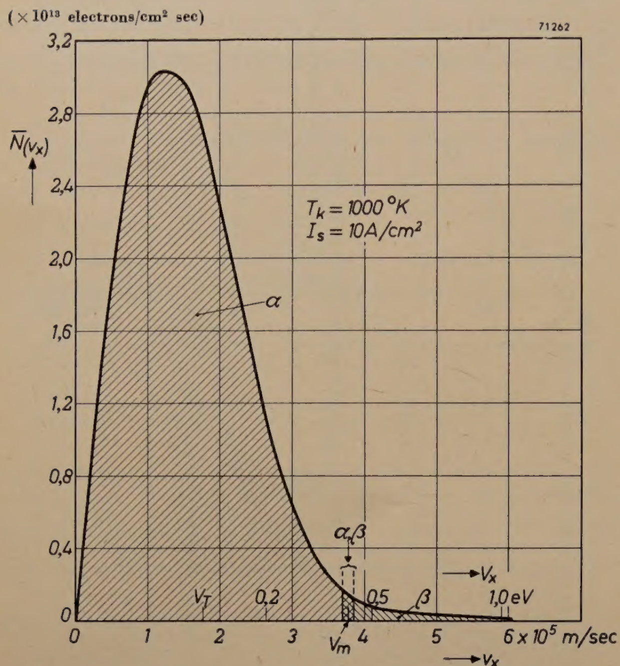

Fig. 8. Velocity distribution, according to formula (5), of electrons leaving the cathode. The mean velocity corresponds to V_T (expressed in electron-volts). The numbers given are practical figures. The majority of the electrons do not reach the anode (a-electrons); those which do reach it are much fewer in number (β-electrons). The a-β-electrons have velocities within the transitional zone between the a- and the β-electrons — round about the velocity v_m, which is related to the depth of the potential minimum V_m as $v_m = \sqrt{2eV_m/m}$. The behaviour of these electrons is greatly affected by fluctuations in the depth of the potential minimum. v_x is the forward electron velocity. The lower horizontal scale gives v_x in metres/sec, the upper one the corresponding energy V_x in electron-volts.

back, the longer this shallow part becomes. If there were no fluctuations in the minimum, the electrons which just managed to reach it would have an infinitely long transit time.

In addition to the current pulses already described also secondary current pulses occur, owing to a temporary lowering of the potential minimum during the time that an a-electron is close to it. As a result there is a temporary increase in the number of electrons forced to return to the cathode. This phenomenon will be referred to again later.

2) β-electrons — electrons leaving the cathode at such a velocity as to be able to pass the potential minimum. These electrons are therefore responsible for the anode current I_a. The current pulses resulting from the β-electrons have the shape depicted in fig. 9*b*. After leaving the cathode such an electron is decelerated, but once it has passed the potential minimum (at the moment $\tau_{\beta m}$) it is accelerated until it reaches the anode (at the moment $\tau_{\beta m} + \tau_{\beta a}$). Since these electrons, too, temporarily deepen the potential minimum, they will also give rise to secondary current pulses.

3) a-β-electrons — these are the electrons leaving the cathode with velocities round about the boundary velocity between a- and β-electrons, which corresponds to the potential V_m in fig. 8. These electrons are highly sensitive to small variations in the depth of the potential minimum, such as may arise, for instance, from slight variations in the anode voltage. Though few in number, they nevertheless have a considerable influence upon the properties of the valve; for example, they determine the increase or decrease of anode current when the anode voltage varies. It may, therefore be said that the a-β-electrons are responsible for the static (low-frequency) internal resistance of the diode.

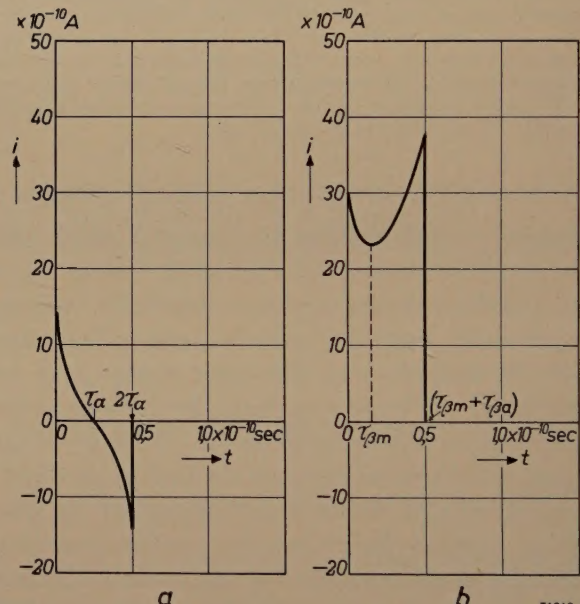

Fig. 9. (a) Shape of the current pulse generated by an a-electron in the external circuit of a diode with space charge. (b) The same for a pulse generated by a β-electron. The symbols are explained in the text.

Fluctuations in the potential minimum; secondary current pulses

When there is one a-electron in transit in addition to the average number of electrons, and particularly when that electron stays in the vicinity of the potential minimum (round about τ_a in fig. 9a), the depth of that minimum changes, as indicated in *fig. 10* [9]). Where, in the following, mention is made of the influence of one single electron, it

should be taken as the average influence for a group of electrons all under practically the same conditions. There are in fact so many electrons leaving the cathode per second that they may be considered as being in groups within which there are only negligible differences in initial velocity and the instant of emission. The movement of such a group therefore influences the anode current: more α-β-electrons turn back. Its effect is equivalent to two secondary current pulses in the external circuit, firstly that caused by a temporary shortage of traversing electrons (i.e. by "holes" starting in the minimum and moving towards the anode in a more than linearly accelerating field, with transit time $\tau_{\alpha\beta a}$), and secondly that caused by an equally large surplus of returning electrons (moving towards the cathode in a more than linearly accelerating field, with transit time $\tau_{\alpha\beta c}$). These two current pulses are represented diagrammatically by curves *I* and *II* respectively in *fig. 11a*. Both the "holes" and the surplus electrons stay in the vicinity of the potential minimum a relatively long time, so that $\tau_{\alpha\beta a}$ and $\tau_{\alpha\beta c}$ are much greater than $\tau_{\beta a}$ and τ_{α}.

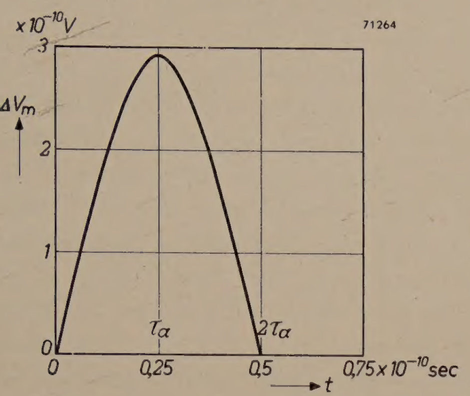

Fig. 10. An α-electron moving somewhere between anode and cathode (transit time $2\tau_{\alpha}$) causes a gradual change ΔV_m to take place in the depth of the potential minimum.

[9]) Except for the sign, a shortage of emitted electrons causes the same phenomena as a surplus. Since it is the fluctuations that are being considered here, the sign is immaterial. In addition to the fluctuations in depth of the potential minimum, fluctuations also occur in its position. The latter, however, produce effects of a higher order, which can be left out of consideration here.

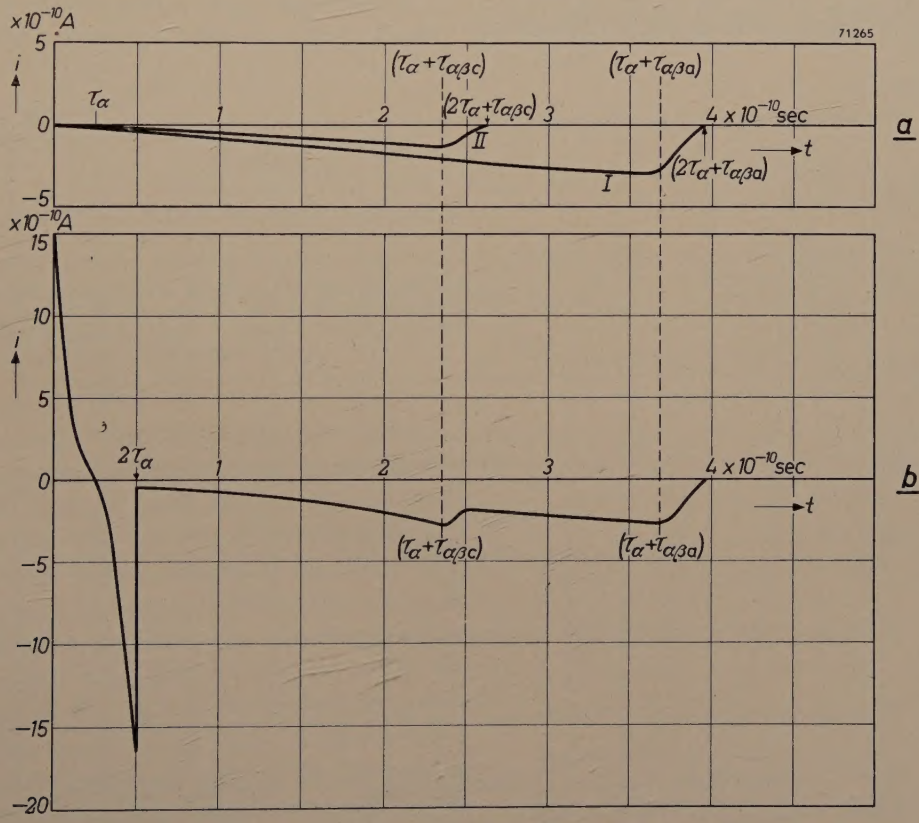

Fig. 11. (a) As a result of the change in depth of the potential minimum, fewer α-β-electrons reach the anode. This may be represented (*I*) by a stream of „holes" moving from the potential minimum towards the anode (with transit time $\tau_{\alpha\beta a}$ ($> \tau_{\alpha}$)), commencing perceptibly at the moment τ_{α} and rapidly decreasing after a time $\tau_{\alpha} + \tau_{\alpha\beta a}$ (with decay time τ_{α}); and (*II*) a stream of additional electrons returning to the cathode with a transit time $\tau_{\alpha\beta c}$($> \tau_{\alpha}$). This current also begins to become of importance after τ_{α}, and continues for an interval of time $2\tau_{\alpha} + \tau_{\alpha\beta c}$. ($b$) The composite (total) current pulse produced by an α-electron in the external circuit. This is practically identical to the primary current pulse of fig. 9a, but has a small surplus on the negative side. Here this surplus is greatly exaggerated.

Since but few α-electrons penetrate to close to the minimum, the amplitude of the pulses *I* and *II* is only small compared with the primary pulse of the α-electrons, especially when the anode voltage is not too low (little space charge). The total current pulse of the α-electrons is then practically equal to the primary pulse; it is represented in fig. 11*b*. The resulting area below the curve is practically equal to zero. This means that at low frequencies the amplitude of the Fourier spectrum is almost zero. There is, however, a small excess below the axis, which represents the very weak total-emission noise at low frequencies. From fig. 11*b* it can be seen that for high frequencies the pulse has an A.C. character, a wave with a cycle of about $2\tau_a$ predominating. The Fourier spectrum of this pulse shows large amplitudes at frequencies in the order of $1/(2\tau_a)$, which is mostly in the centimetric wave range. Relatively large alternating currents with such frequencies therefore arise in the external circuit and cause noise, which is called the high-frequency total-emission noise [10]).

[10]) A. van der Ziel and A. Versnel, Philips Res. Rep. 3, 13-23, 1948; J. J. Freeman, J. Res. Bur. Standards 42, 75-88, 1949.

When, during their transit time, electrons returning to the cathode stay in an external alternating field having a period of oscillation that is no longer very small compared with the transit time, their movements give rise to periodical variations in the rhythm of that field. As a result, alternating currents of the same periodicity are induced in the external circuit. These currents are, as a rule, phase-shifted with respect to the external alternating field and constitute a load on the voltage source producing that field. Owing to the phase shift the load can be regarded as a complex admittance, the total-emission admittance, the real part of which is called the total-emission conductance.

This conductance may be considered as being an equivalent noise resistance, which is responsible for the total-emsission noise. It is then found that this resistance has an equivalent temperature equal to the cathode temperature — not surprisingly considering that the α-electrons are practically in thermal equilibrium with the cathode.

A β-electron also brings about a change in the depth of the potential minimum — a change much

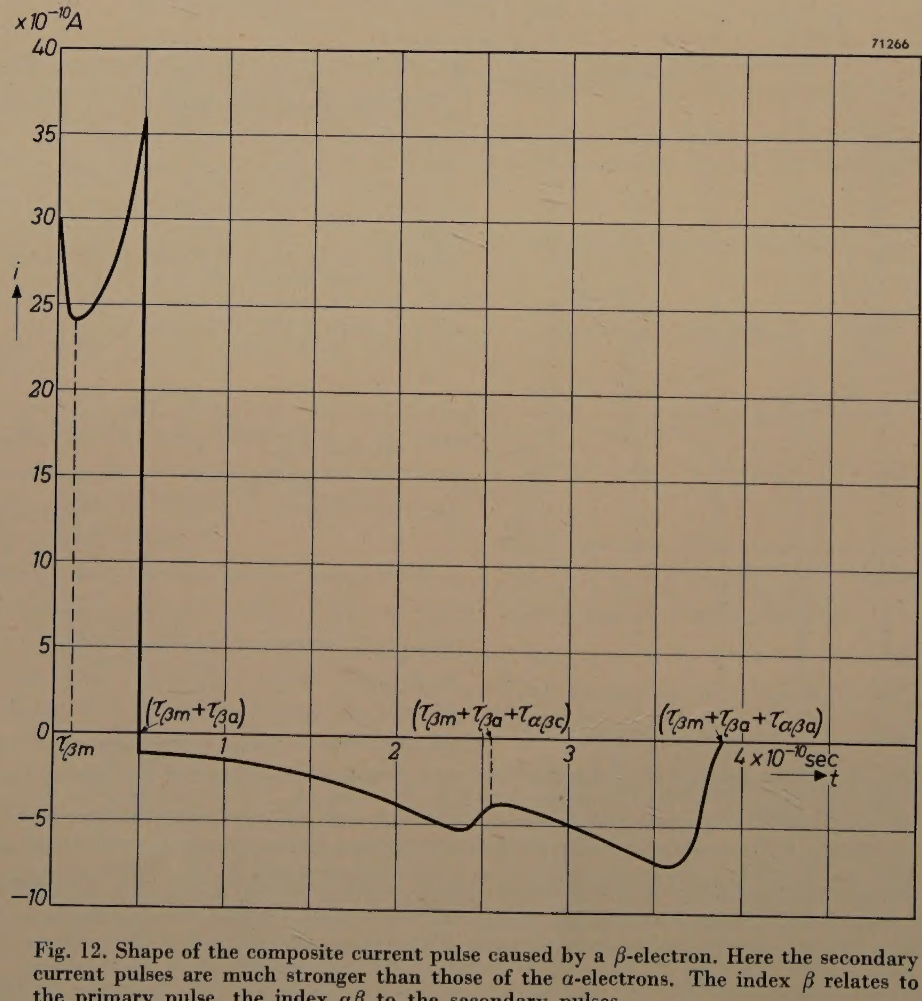

Fig. 12. Shape of the composite current pulse caused by a β-electron. Here the secondary current pulses are much stronger than those of the α-electrons. The index β relates to the primary pulse, the index $\alpha\beta$ to the secondary pulses.

greater than that caused by an α-electron, because on an average β-electrons stay much longer in the vicinity of the minimum. The secondary current pulses produced by the β-electrons are practically identical in shape with those of fig. 11*a*, but of much greater amplitudes, in accordance with the above comments. The shape of the composite β-current pulse — primary and secondary together — is represented in *fig. 12*. Averaged over various initial velocities, the area of the curve above the axis is practically equal to that below the axis, as it was for α-electrons. Here this is due to space charge, but the effect is similar: at low frequencies the β-electrons cause practically no noise. The Fourier spectrum of the β-pulses contains, however, strong

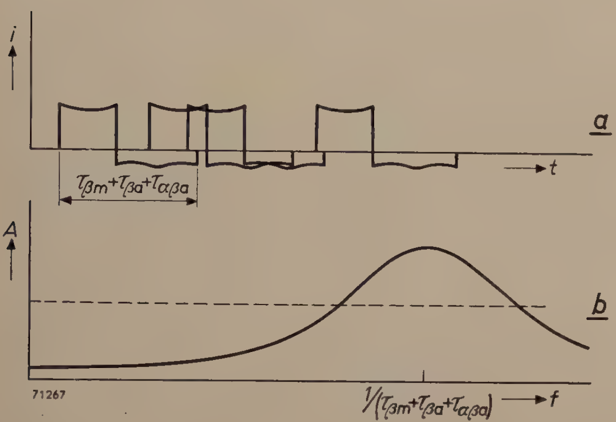

Fig. 13. As in fig. 6, but for a diode with space-charge suppression. (*a*) Shape of the current pulses (see fig. 12), (*b*) noise spectrum. At low frequencies the noise is much weaker than the non-suppressed noise in fig. 6*b* (denoted by the broken horizontal line), but at frequencies in the order of the reciprocal transit time it may increase to about twice that value. At still higher frequencies it decreases again.

components near the high frequency $f = 1/(\tau_{\beta m} + \tau_{\beta a} + \tau_{\alpha\beta a})$, so that at that frequency the β-electrons do yield an appreciable contribution towards the noise. In *fig. 13a* a series of overlapping (β-) pulses have been drawn, similar to fig. 6*a*, whilst fig. 13*b* represents the corresponding noise spectrum. Owing to noise suppression, the intensity at low frequencies is less than that according to fig. 6*b*. At frequencies in the order of the reciprocal transit time, however, the intensity may be about twice that of the non-suppressed noise of fig. 6*b*, because of the special waveform of the pulses. At still higher frequencies the intensity again approaches zero.

The conclusion to be drawn from all this is that, owing to the influence of the electrons upon the potential minimum, electronic valves will show more noise at very high frequencies than at intermediate ones. This is borne out by experimental facts, as is illustrated in *fig. 14*.

Transit-time functions in a diode

In the foregoing we have investigated the shape of the current pulses induced in the external circuit by the movement of electrons inside the valve. Fourier analysis of these current pulses revealed that at frequencies in the order of the reciprocal transit times of the electrons inside the valve, the noise in the external circuit is stronger than at lower frequencies. Nothing can be said against this method physically, but it does not lend itself well to quantitative calculations, and for that reason an approximative method is often employed.

First a Fourier analysis is made of the convection-noise current i_{con} caused by the electrons leaving the cathode. From the spectrum a component $i_{con}(f)$ of a certain frequency is then chosen and its relationship to the noise-current component $i(f)$ of that frequency in the (short-circuited) external circuit investigated. This relation is given by a transit-time function Ψ_1 defined as:

$$i(f) = i_{con}(f)\Psi_1.$$

Ψ_1 is a complex function of the argument j$f\tau$, where τ stands for the average transit time from cathode to anode.

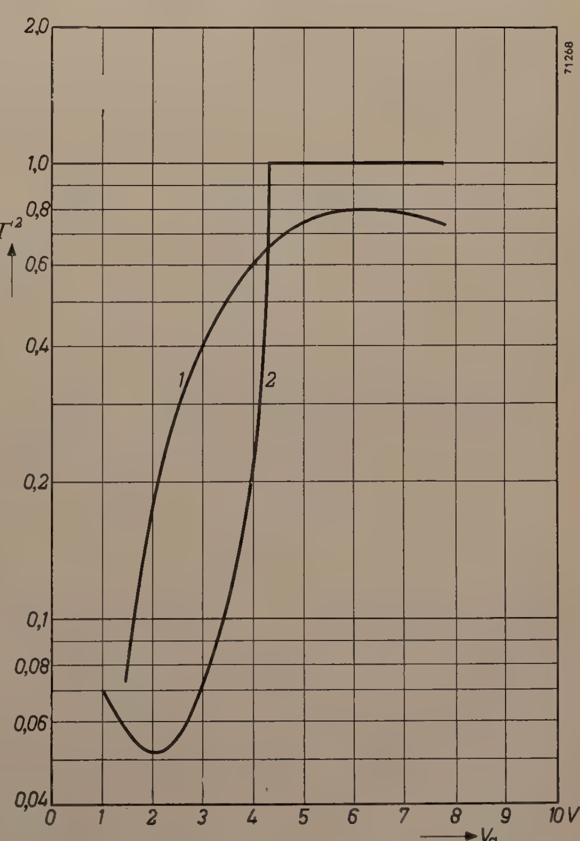

Fig. 14. The experimental value of Γ^2 for an experimental diode with L-cathode at a wavelength of 3 cm (curve *1*) and at moderate anode voltages is much higher than the theoretical value at low frequencies (curve *2*).

When calculating Ψ_1 it is mathematically very difficult, if not impossible, to take into account the interaction between the electrons near the potential minimum. But after certain simplifications, among them the assumption that the initial velocities of the electrons may be ignored, it is possible to compute Ψ_1 [11]).

An alternating signal voltage across the valve will influence the depth of the potential minimum, and set up an alternating convection current I_{con}. This produces an alternating signal current I in the external circuit, which can also be expressed in terms of I_{con} with the aid of a transit-time function. This function, Ψ_2, differs from Ψ_1 in that the electrons are here moving in an alternating potential field whose phase bears a certain relationship to the phase of I_{con}. The noise currents, on the other hand, bear no relationship at all to the signal voltage. The transit-time function Ψ_2 has been calculated with the aid of the approximation mentioned above. For a better approximation the static depth and the position of the potential minimum have sometimes been taken into account, but the high-frequency fluctuations in the potential minimum have hitherto always been ignored [12]).

Notwithstanding these approximations, transit-time functions have proved to be very useful in practice, but when applying them one should always take the results *cum grano salis*.

What has been said here about the diode applies also to valves with more electrodes, such as the triode, but then the noise phenomena are influenced to a much greater extent by the circuit in which the valve is incorporated. The mutual influence of the currents in the input and output leads varies according to the nature of the circuit. In the case of a triode it appears to be possible for the circuit to be so arranged that the noise is partly compensated by this mutual influence, but such compensation is out of the question for a diode, since it has only one external lead. The noise of a triode will be discussed in another article to follow. It will be seen then that, though the complexity of the problem makes it necessary to employ the method of approximation with the aid of transit-time functions, it is possible nevertheless to draw very important conclusions for practical purposes.

[11]) C. J. Bakker and G. de Vries, Physica 2, 683-697, 1935.
[12]) A. van der Ziel, Wireless Eng. 28, 226-227, 1951.

Summary. Following upon a review of the various causes of noise inside and outside a radio receiver, a closer study is made of the noise resulting from the movement of electrons in a diode (electronic noise). At not too high frequencies (lower than 10^7 c/s) there are a number of causes of noise, amongst others the shot effect, which are briefly discussed. The influence of possible space charge upon the potential distribution in the valve, and thus upon noise is investigated. At frequencies round about 10^8 c/s and higher, where the transit times of the electrons can no longer be regarded as being infinitely short, other noise phenomena arise. These are related to the finite width and special shape of the current pulses generated by individual electrons in the external valve leads. This causes, among others, total-emission noise. At very high frequencies signal currents also are subject to the influence of the finite width of the current pulses of which they are composed, and one of the results of this is an increase in the input conductance (total-emission conductance). Consideration is given to the different behaviour of noise currents and signal currents in the valve. Both these kinds of current can be approximately determined by means of (different) transit time functions.

AN EXPERIMENTAL X-RAY APPARATUS WITH MIDGET X-RAY TUBE

by P. J. M. BOTDEN, B. COMBÉE and J. HOUTMAN.

621.386.1:615.849:620.179

The small, mass-produced and inexpensive high-tension generator of a projection television receiver has been found to be a most suitable voltage supply unit for a very small X-ray tube. The present article shows how this fact was made use of when the "KT" apparatus was developed. The X-ray tube of this apparatus is not only remarkable for its small size, but also for a directional effect in the emitted radiation, favourable to therapeutic application, which effect is not observed in normal X-ray tubes.

Introduction

The X-ray tube which we will discuss in the present paper is probably the smallest ever designed. It is 45 mm long and 14 mm in diameter, including the earthed jacket. A power of 2.5 watts can be dissipated continuously at the anode, the maximum tube voltage is 25 kV, and the maximum tube current 200 μA. To complete this brief description, *fig. 1* shows a photograph of the tube (which has not yet been brought into regular production), with the cable connecting it to the high-tension source. The larger tubular element at the left end of the cable is not the X-ray tube, but the plug.

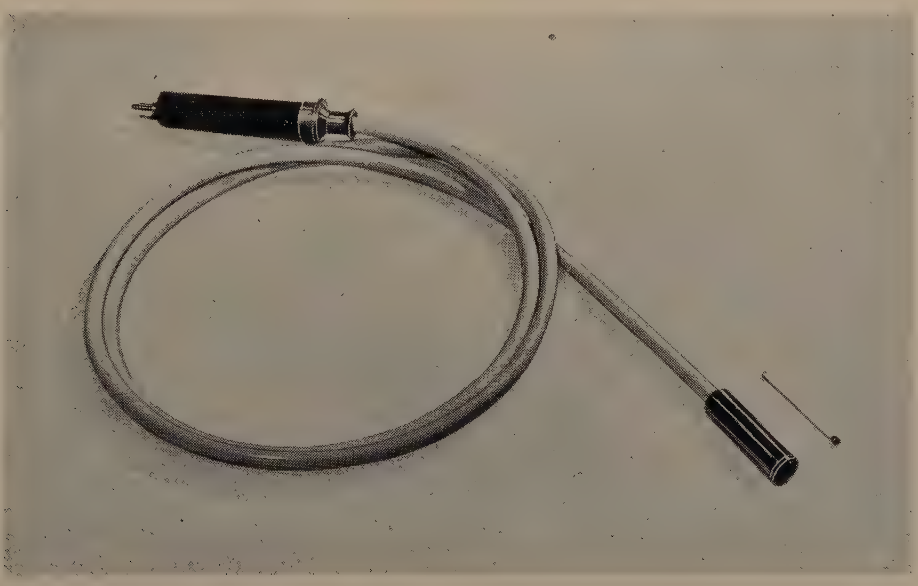

Fig. 1. Midget X-ray tube (KT tube) with cable and plug. A match is shown by the side of the X-ray tube (to the right) for comparison.

A few remarks will show that the design of this midget X-ray tube (and the accessory high-tension source) was not merely inspired by an ambition to design tbe smallest X-ray tube of the world. In certain therapeutic applications of X-rays it can be most useful to the physician to have an X-ray source at his disposal, of such small dimensions that it can easily be held and positioned by two fingers, and which can be inserted into small cavities of the body if necessary. Sometimes radiographs of all sorts of objects have to be made for research or teaching purposes, where a very soft radiation is required, an extremely small power is sufficient and a high price for the apparatus is undesirable. This defines in general terms the possible application of the above characterised "KT" tube and "KT" apparatus (from the Dutch for "smallest therapy", viz. "kleinste therapie"). We shall discuss below the special features of this X-ray source, and those it lacks; it is convenient to compare it with the CT tube

(CT from Contact Therapy), described previoulsy in this review, which, of all X-ray tubes is most similar to the tube under discussion [1])[2]).

We shall conclude the present paper with a few further observations on the possibilities of application.

Construction of the X-ray tube

In *fig. 2* a schematic sectional view of the tube is given. The simplicity and compactness of design shown by the figure are chiefly due to the fact that the X-rays leave the tube via the anode. For this

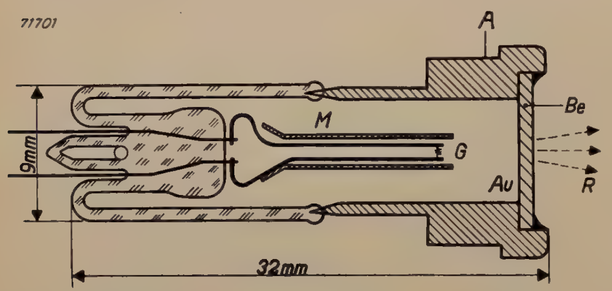

Fig. 2. Schematic cross-section of the KT tube. *A* anode can, *Be* beryllium plate, *Au* gold layer, *G* filament, *M* metal cylinder, *R* effective X-ray beam.

purpose the anode consists of a very thin layer of gold deposited on a vacuum-tight plate of beryllium. Due to the very high atomic number of gold (79) a high efficiency of X-ray production is obtained from the electrons slowed down in it; owing to the very low atomic number of beryllium (4) this will transmit the soft radiation excited at 25 kV with negligible attenuation. The gold layer has to be very thin in order to restrict the proper absorption of the excited X-radiation to a minimum; on the other hand it should not be too thin, since all electrons passing through the gold layer are naturally lost for the generation of X-rays.

The "inherent filter" of the X-ray tube, i.e. the filter which the X-rays, produced by the tube designed in the manner given above, must pass before their practical application, is equivalent to about 1.5 mm beryllium. The importance of this very low inherent filter will be discussed presently.

The beryllium plate is soldered in a metal bush which functions as tube wall for this end of the tube ("anode can"). This metal anode assembly is earthed and the cathode is connected to high voltage. The cathode comprises a filament, consisting of a tungsten coil of a few turns, and a small metal cylinder enclosing the filament and its supporting poles. This cylinder has a focusing effect on the electrons emitted by the filament. Moreover, it simplifies the problems of the insulation between the cathode and the closely adjacent earthed jacket: without the cylinder the electric field strengths at the thin lead-in poles would be much higher than they now are on the cylinder.

The filament heating power can amount to about 1 watt at the highest (1.4 V, 0.6 A). The coilled filament will then give a saturation emission of 200 μA.

The focus and the radiation obtained

A description of an X-ray tube is not complete without some remarks regarding the configuration and the loading of the focal spot. In this case it is most appropriate to begin with some general observations, which will also explain the choice of the constructional principle adopted.

Soft radiation is suitable for the therapeutic irradiation of very thin layers of tissue on or at the surface of the body. The underlying healthy tissue receives only relatively small doses in this case and is consequently very little affected (small depth penetration). Owing to the low voltage and the very small inherent filter, the radiation of the tube is extremely soft; the half value thickness of the radiation is only 0.035 mm of aluminium or 0.5 mm of tissue at a tube voltage of 25 kV, and at 10 kV it is even 0.02 mm of Al or 0.3 mm of tissue. In this respect the radiation is similar to that of the present CT tube with a window of mica and beryllium (see the article referred to in note [2])).

A second means of obtaining a very small depth penetration is to place the focus of the X-ray tube at a very short distance from the skin. This was extensively commented on in the article referred to [1]). This same article further stated that the smallest focus-skin distance, and therefore the smallest relative depth doses can be realised if the anode itself serves as exit window for the X-rays. This design principle also leads to a relatively simple tube construction. It is generally considered to be a drawback to this principle of design that the rays passing obliquely through the anode are attenuated more than those passing through perpendicularly, resulting in a strong decrease of the dosage rate from the centre to the edges of the irradiated area. This makes it difficult to apply an exact dosage of radiation. For this reason a different design was chosen for the CT tube, as may be seen in the article mentioned [1]).

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[1]) H. A. G. Hazeu, J. M. Ledeboer and J. H. van der Tuuk, An X-ray apparatus for contact therapy, Philips Techn. Rev. **8**, 8-15, 1946.
[2]) B. Combée and P. J. M. Botden, Special X-ray tubes, Philips Techn. Rev. **13**, 71-80, 1951 (No. 3).

We have, nevertheless, already observed that the design with anode functioning as window was chosen for the KT tube. This does not imply, however, that the objection referred to above was ignored; surprisingly enough this objection does not hold at all in this case! If the radiation intensity of the KT tube is measured in various directions [3], a diagram as given in *fig. 3* results. The intensity by no means decreases with increasing deviation from the axial direction, but even increases initially; at an angle of 20° to the axis it is at its maximum, and the subsequent decrease is still rather gradual up to angles of about 50°. There is thus no question of a strong decrease in the dosage rate over the irradiated area from the centre to the edges. On the contrary, a very uniform dosage distribution is found for not too large, flat areas, even more uniform than with the spherical radiation diagram of normal X-ray tubes, since in our case the larger distance from the focal spot to the off-axis parts of the field is neutralised by the initial increase in intensity shown in fig. 3.

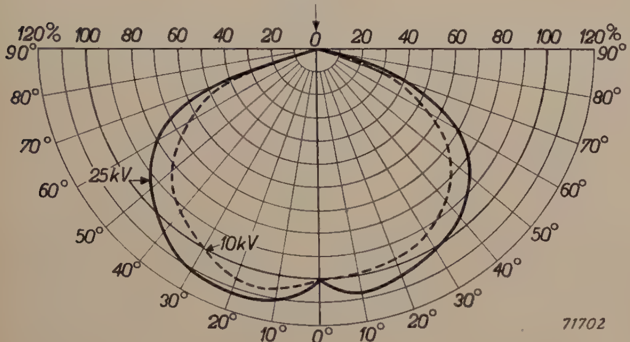

Fig. 3. Relative dosage rate of the KT tube, measured in different directions from the axis, at a distance of 150 mm from the focus, for two different tube voltages. In the axial direction (0°) the dosage rate for both curves is made equal to 100. The asymmetry may be due to a slight inhomogeneity of the gold layer. (These measurements and those of fig. 4 were made by Dr. W. J. Oosterkamp and J. Proper.)

The phenomenon illustrated by fig. 3 has been known for a long time, and can be explained by a consideration of the mechanism whereby X-rays are produced in the anode. It is not observed in normal X-ray tubes because of the rather thick anode these tubes always contain. In the present case only the very thin foil of gold functions as an anode, and as a matter of fact Kulenkampff was able to demonstrate the directional effect as early as in 1928 by the use of specially designed tubes with a very thin anode [4].

[3]) For these measurements see: W. J. Oosterkamp and J. Proper, Acta Radiologica **37**, 33-43, 1952 (No. 1). Therein is given a full description of the method whereby such soft and heterogeneous X-rays may be measured.

[4]) H. Kulenkampff, Ann. Physik IV, **57**, 597, 1928. For more recent investigations into the phenomenon see: G. Sesemann, Ann. Physik V, **40**, 66, 1941; O. Blunck, Ann. Physik. VI, **9**, 373, 1951.

The electrons striking the anode with great velocity are slowed down on penetrating into the metal. According to classical theory, each electron will emit radiation, the continuous X-radiation or "Bremsstrahlung". According to this theory one can also expect the radiation to have zero intensity in the direction of movement of the electron, as also in the reverse direction, whereas the radiation will be at its maximum at a certain angle to this direction — depending on the electron velocity. In a thick anode a penetrating electron may repeatedly change its direction by small amounts, due to deflection by atomic nuclei, with very small loss of energy each time, before it passes a nucleus so closely that it is strongly decelerated and emits the X-radiation observed. The contribution to the radiation, of this electron, will in that case possess the directional dependence as mentioned above, but with its last direction of movement as axis. Since these axes, for all the electrons, will have a random distribution of direction, the total radiation can reveal little or nothing of the described directional effect.

On the other hand, if the anode is very thin, the electrons will already have passed the entire layer after relatively few encounters with atom nuclei. The emission of each contribution to the observed radiation can therefore only be preceded by few deflections; consequently the "axes" for all contributions deviate but slightly from the axis of the X-ray tube, and the total radiation will consequently also show the directional effect with but little spread.

If the anode functions as exit window, the opportunity for the natural directional effect of the radiation to be observed becomes still smaller in the case of a rather thick anode, since the earlier mentioned absorption effect (intensity decrease with increasing angle), especially important in the case of thick anodes, is superimposed on this directional effect. Fig. 3 clearly shows the increasing importance of this effect, even with the very thin anode of the KT tube, as the tube voltage is decreased (softer radiation).

Owing to the constructional principle adopted, it is possible with the KT tube to reduce the focus-skin distance to 1 mm if so desired, viz. by pressing the anode into the surface to be irradiated. Enormous dosage rates can be realised with only a very small power, if the distance between focus and object is so small. With the above-mentioned maximum permissible anode dissipation of 2.5 W and a voltage of 25 kV, the KT tube will give 17 000 röntgen units per minute at a distance of 1 cm from the focus; at 10 kV and 2 W dissipation (the tube current is 200 μA maximum), it will still give 7000 r/min! These are measured values (*fig. 4*); a separately determined correction factor was applied for the absorption of the soft radiation in the window of the dosimeter (see the article referred to in note [3])). At a focus distance of 1 mm even much larger dosage rates, of some hundred thousands r/min, are obtained. Naturally, if the focus distance is not very small, e.g. 20 mm, which can also be reached with the CT tube, the KT tube is, as far as dosage rates are concerned, by far the inferior of the CT tube, which was designed for a maximum power of 100 W and voltages up to 50 kV.

In normal X-ray therapy tubes the focus is made as small as possible in order to obtain a sharp boundary to the field to be irradiated (small penumbra width of diagram edges); in the KT tube, on the contrary, the electrode configuration was so designed as to spread the focus over the entire anode surface (diameter 6.5 mm). Owing to the rather large focal dimensions the loading of 2.5 W is permissible and the above-mentioned very large dosage rates are obtained. It is true that part of the gain with regard to the depth penetration, obtained by the selected principle of construction, is sacrificed if the focus is so large, for if the focus is not small in proportion to the focus-skin distance, the dosage will, for geometrical reasons, not follow the inverse square law, but will decrease much more slowly with increasing distance. Thus, the dosage rate at 1 mm distance will not be 100 times larger but, according to our computation, only 25 times as large as at 1 cm distance. Still, one can see from these figures that the distance effect is still considerable. Moreover, it is enhanced by the effect of the absorption of the rays in the tissue: points at some distance below the skin surface profit less by the largeness of the focus, therefore, than do points on the skin surface (see *fig. 5*). The resulting decrease of the dosage with depth is shown in *fig. 6*. It will be seen, consequently, that only a thin layer of skin of a few tenths of one millimetre is effectively irradiated.

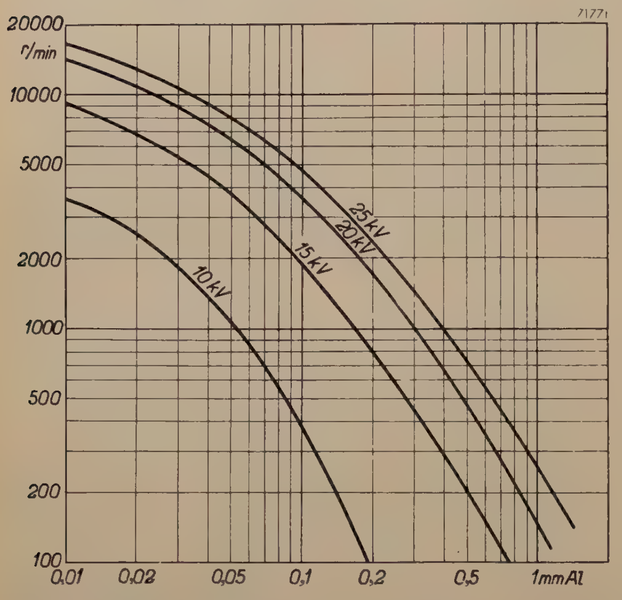

Fig. 4. Absorption characteristic of the radiation of the KT tube. The dosage rate obtained at 1 cm distance from the focus when the radiation is weakened by an aluminium filter of varying thickness is plotted for four values of the tube voltage. The minimum filter, the inherent filter of the tube, is equivalent to about 1.5 mm beryllium or 0.03 mm aluminium. For this case the graph gives a value of 17 000 r/min at 25 kV and 3600 r/min at 10 kV. (The figures along the horizontal axis are not correct: a constant value of 0.02 is to be added to all of them.) All curves were measured at a tube current of 100 μA; the 25 kV curve, therefore, corresponds to a load of 2.5 W, the 10 kV curve to 1 W. The measurements were made at a distance of 2.5 cm from the focus and recalculated to a distance of 1 cm by use of the inverse square law: a correction was made for the smaller air absorption at 1 cm distance as against 2.5 cm distance from the focus.

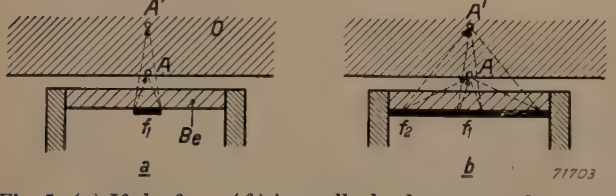

Fig. 5. (*a*) If the focus (f_1) is small, the dosage rate decreases as the inverse square of the distance. The dose thus rapidly decreases from A to e.g. A'. (*b*) If the focus is large, the dosage rate decreases more slowly than as the inverse square of the distance. The decrease is intensified, however, by the extra absorption of oblique rays in the object O: point A' profits less from the largeness of the focus than point A, since the rays originating from f_2 have to travel a longer distance in the tissue than those originating from f_1.

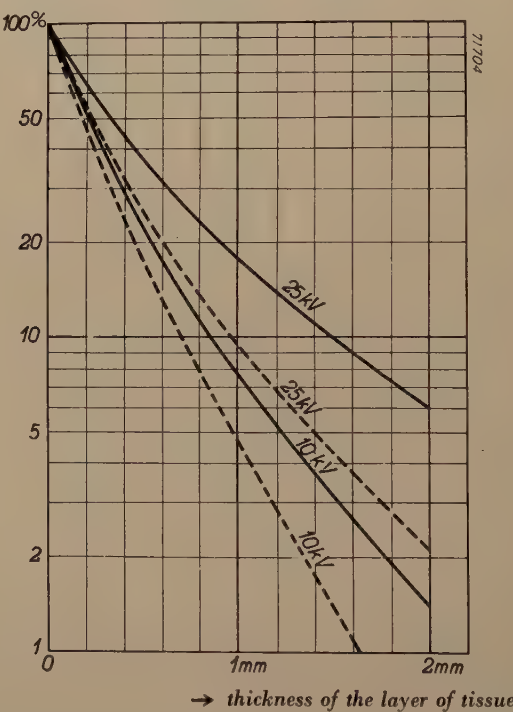

Fig. 6. Dosage rate of the KT tube computed for various depths in the irradiated body, at a focus-skin distance of 1 mm, for two different tube voltages. The dosage rate on the skin was set equal to 100 for both curves. The broken-line curves represent the dosage rate which would be obtained with a point focus.

It will be seen from this, that the lack of sharpness of the field boundary, which was mentioned above as the current objection against a broad focus, will not be of much significance in this case. For this lack of sharpness will only be appreciable in planes at some distance behind the diaphragm, in the case under discussion — the diaphragm being represented by the anode cap placed on the skin — at a certain depth below the skin where the dose is already relatively small.

If the anode is placed on or near to the skin of the patient, the focus is of nearly the same area as the irradiated skin surface. Naturally this is conducive to a still further equalisation of the dosage distribution over the irradiated surface (see above).

The above-mentioned limit of 2.5 watts to the loading of the anode is set by the temperature both of the focus and the jacket. We need not distinguish between continuous and short-duration loading in the case of the KT tube. The heat capacity of the gold foil is so small that the maximum focus temperature is always reached, even in the briefest period of loading likely to be used. The temperature of the outer face of the anode rises in proportion to the time of loading, in accordance with the curve

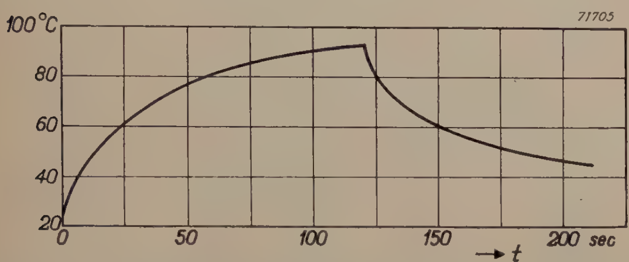

Fig. 7. Temperature time curve for the outer surface of the anode of the KT tube in free air under load. The tube was loaded to 2.5 W from $t = 0$ to $t = 120$ sec, the tube then being switched off. (If the anode is placed on the skin of the patient, the temperature will rise a little more slowly, owing to the thermal conductivity of the body.)

represented in *fig. 7*, which shows that on prolonged loading temperatures not much higher than 90 °C are reached. This temperature is, of course, too high for direct contact with the skin of the patient, so that irradiation in this manner is limited to 10 or 20 seconds — which will, however, in general be amply sufficient for the application of the necessary dose!

For irradiation at a certain, albeit small, distance (in which case e.g. a small localizer is fitted to the tube) the anode temperature is not at all important. At other places, the jacket, which, if the tube is fully loaded, has to dissipate 3.5 watts in total (2.5 W from the anode, 1 W from the cathode), becomes hardly warmer than the hand, and it can therefore be held by the fingers without discomfort, or allowed to touch the skin or the mucous membranes if tissue parts in body cavities have to be irradiated.

Jacket and cable

The position of the X-ray tube in the jacket into which it is built, is shown in *fig. 8*. The tube is connected to the high-tension source by means of a very flexible cable 1.5 metre long, with "Podur" (polyvinyl chloride) insulation and a metal braiding. The metal jacket is bonded to this braiding at one end and fixed at the other end to the anode can. Thus the anode is earthed via the braiding.

A second protective "Podur" sleeve is drawn over the metal braiding and makes a liquid-tight seal with the metal jacket. The X-ray tube can therefore be easily disinfected, which is necessary for application in body cavities. The total diameter of this very flexible cable, built up as described, is only 8 mm.

The thin cable stands up very well to the high voltage to which it is subjected. The X-ray tube is operated by D.C. voltages up to 25 kV; it has been shown that the free cable (i.e. without X-ray tube) does not break down, even if subjected to a direct voltage of 150 kV at room temperature. When subjected to alternating current, which is always much more dangerous to cables, the test showed that the cable could stand a voltage of 60 kV peak value for thirty minutes without breaking down.

The high-tension generator

In developing the KT apparatus we have been able to avail ourselves of an earlier development in the field of television. A high-tension generator had been developed in Eindhoven for supplying the cathode-ray tube used in projection television [5]), possessing exactly the properties we needed for the KT tube supply. This generator produces a well smoothed direct voltage of 25 kV at a load of 150 μA, its characteristic being such that the short-circuit current is not much greater than the normal working current, and the output capacitance is only small, so that the energy which will be discharged through the cathode-ray tube in the event of a fault (breakdown) is not excessively large. The last two properties, all important to the avoidance of overloading of the fluorescent screen, are also essential to our purpose; it is obvious that all overloading of the very small KT tube, however short, should be avoided.

We have consequently been able to copy, in broad outline, the design of the high-tension generator referred to, which has already been described in this review. In the present article, therefore, we shall give only a résumé of the principle and mention the deviations from the earlier construction which were found to be necessary.

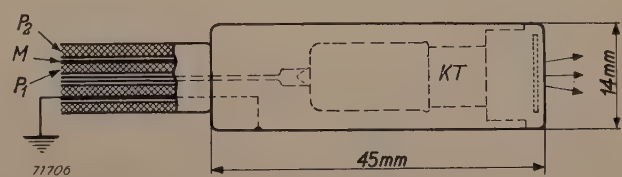

Fig. 8. Position of the X-ray tube (*KT*) in the jacket, and sectional view of the cable. P_1 "Podur" insulation, *M* metal braiding, P_2 outer "Podur" sleeve.

[5]) Projection-television receiver, III: G. J. Siezen and F. Kerkhof, The 25 kV anode voltage supply unit, Philips techn. Rev. **10**, 125-134, 1948.

An oscillator circuit, consisting of a coil L and its own capacitance C_p, is built into the anode circuit of a pentode. The anode current is periodically interrupted by a saw-tooth voltage applied to the grid of the pentode. At each interruption a damped oscillation occurs in the circuit with a peak value:

$$V_{max} = i_{max} \sqrt{L/C_p};$$

i_{max} is the anode current at the moment of interruption. With suitable circuit constants, a voltage peak of the order of 10 kV can be obtained and the interruption can be given a rather high rate of repetition, e.g. of the order of a 1000 times a second. The intermittent high voltage in the oscillator circuit is converted by a cascade rectifier, composed of a number of valves and capacitors, into a direct voltage which is a multiple of V_{max}, viz., in our case, 25 kV.

The rather high repetition frequency mentioned above is one of the essential items of the design. As a consequence of this high frequency the resulting direct voltage can be well smoothed with a relatively small capacitance. This amounts to about 2000 pF; the ripple in the voltage on the X-ray tube, at 200 μA tube current, is only about 100 V.

The television generator supplies a positive voltage of 25 kV relative to earth. We needed a negative voltage for the KT tube; this can be obtained by merely reversing the valves in the cascade rectifier.

For the television tube a fixed voltage of 25 kV is required. In our case it was desired that the X-ray tube should also be operable at lower voltages. We have obtained a continuously adjustable tube voltage by making the anode voltage of the pentode variable: this involves variation of the anode current i_{max} at the moment of interruption and, consequently, V_{max} (see the formula given above).

In the television generator the cathode filaments of the cascade valves are fed from a winding coupled to the coil (L) in the anode circuit, and consequently supplying a fixed voltage. In our case the voltage on the coil is variable, preventing the use of this simple method; we had thus to provide for the valves a separate filament transformer, with high tension insulation. We have so arranged it, however, that this transformer is switched on and off simultaneously with the high tension. The service life of the valves is therefore not unduly shortened by useless burning. The resulting slight delay in the excitation of X-rays due to the filaments of the valves first having to be heated and the capacitors to be charged, after switching on the high tension, was not considered objectionable in this case; it amounts to less than ½ second. The filament transformer for the X-ray tube cathode is also switched on and off simultaneously with the above-mentioned filament transformer. Consequently no heat is generated in the tube so long as it is not under high tension and the temperature of the jacket does not rise unduly from its initial value. By means of an adjustable resistor in series with the last-mentioned filament transformer, the current in the X-ray tube can be continuously varied from 0 to 200 μA.

Adjustments of tube current and tube voltage are not completely independent of each other; moreover, no coupling has been provided between the two adjustments to preclude the possibility of the maximum voltage (25 kV) or the maximum power (2.5 W) being exceeded. Such refinements would have made the apparatus too complicated and expensive, in view of its restricted purpose. The only consequences for the user are that he should bear in mind the limit of 2.5 W when selecting the values of the tube current and tube voltage and that he should consult a set of calibration curves when presetting these values (see *fig. 9*). If the user intends to raise the voltage whilst the apparatus is in use, he should adjustt he tube current to the new, smaller value beforehand.

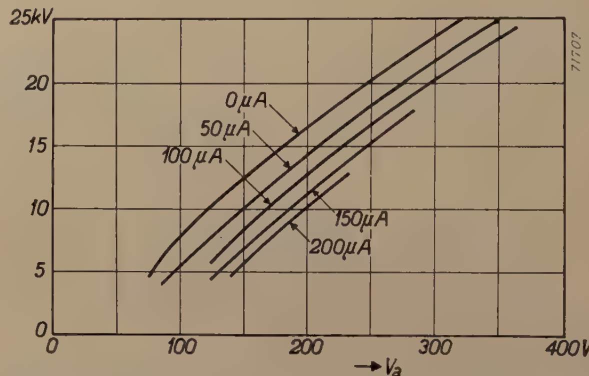

Fig. 9. Calibration curves for the voltage regulation of the KT apparatus. The high tension on the KT tube is varied by adjustment of the pentode anode voltage V_a. The relationship between the two depends also, however, on the tube current, which is separately controlled. — This calibration chart can be made identical for all KT apparatus by means of a variable resistor.

The high tension generator was built into a cabinet, shown in *fig. 10*, together with the requisite power supply apparatus, controls, switches, etc. The cable, with the attached X-ray tube, is connected to it by means of a plug, insulated for high tension, which is tightened by means of a coupling nut. This nut at the same time presses on a pin, which first connects the braiding of the cable (and consequently the anode and the jacket of the X-ray tube) with the earth of the apparatus and then closes the anode circuit of the pentode. A small cylindrical opening to hold the X-ray tube when not

in use has been provided in the lid of the cabinet (in the photograph the tube is just being withdrawn).

Fig. 11 shows the cabinet with side walls removed.

We shall merely mention here three cases for which the apparatus has proved its usefulness: (1) the irradiation of warts and haemangiomae (benign tumors of the blood vessels), more especial-

Fig. 10. The KT apparatus, ready for use. The tube current and the tube voltage are adjusted by means of the control knobs and meters. Note the connection of the "Podur" cable, with the midget KT tube at its end, to the apparatus. When not in use, this tube is housed in an opening in the apparatus.

Methods of application

Physicians who have been working with the KT apparatus for a number of months will presently report elsewhere on its use for therapeutic irradiation.

ly the so-called strawberry marks (*fig. 12*); in most cases of this type the patients are very young children, also incubator children, and the relatively small CT tube is still too large to be convenient in such cases; (2) the irradiation of the cornea of the eye,

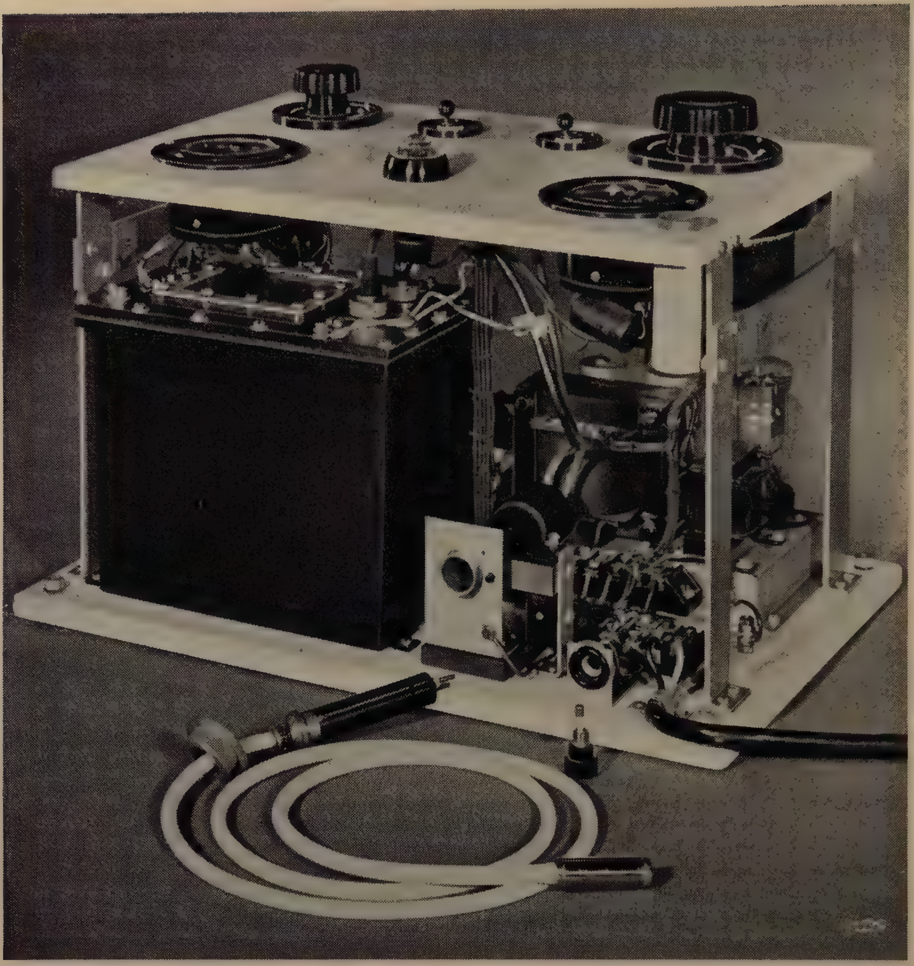

Fig. 11. The apparatus open. The black box on the left contains the high-tension coil and the cascade rectifier. On the right to the rear the power unit supplying the pentode. Shown in the foreground are the unscrewed coupling nut and the plug (withdrawn), by means of which the cable is connected. To the right of this is a safety fuse shown unscrewed.

e.g. after transplantation (*fig. 13*), and (3) the irradiation of very superficially located small tumours of the mouth and throat cavities. For each of these cases special small localizers for the limitation of the field may be useful, and aluminium filters of various thicknesses may be put in the localizers if in a special case a somewhat harder radiation is required.

The KT tube can also be usefully employed in another field, viz. the testing of materials. In support of this observation we may mention the fact (though this can hardly serve to justify its own existence!) that the KT tube renders good service in the production of — KT tubes; the rolled beryllium plate for the anode is tested for the absence of impurities, and the thin layer of gold for homogeneity, in both cases by making X-ray photographs with the KT apparatus. In general the very soft (and not unduly intense) radiation of the KT tube can be employed to good advantage for the examination of very light material or very thin layers.

Lastly, the KT tube may in our opinion be extremely useful in the biological field. An

Fig. 12. Application of the KT tube for the irradiation of a strawberry mark. (This photograph was put at our disposal by Dr. G. J. van der Plaats, radio-therapeutist at the hospital of St. Annadal, Maastricht.)

interesting example is the examination of the effect of X-rays on bacteria or other organisms present in a liquid solution. The KT tube provides a neat way of doing this; the tube is dipped in the solution which is stirred until — according to the laws of probability — each volume element of the liquid has been near the anode for a sufficiently long time to absorb the required total dose. A more obvious application of the KT apparatus is the making of

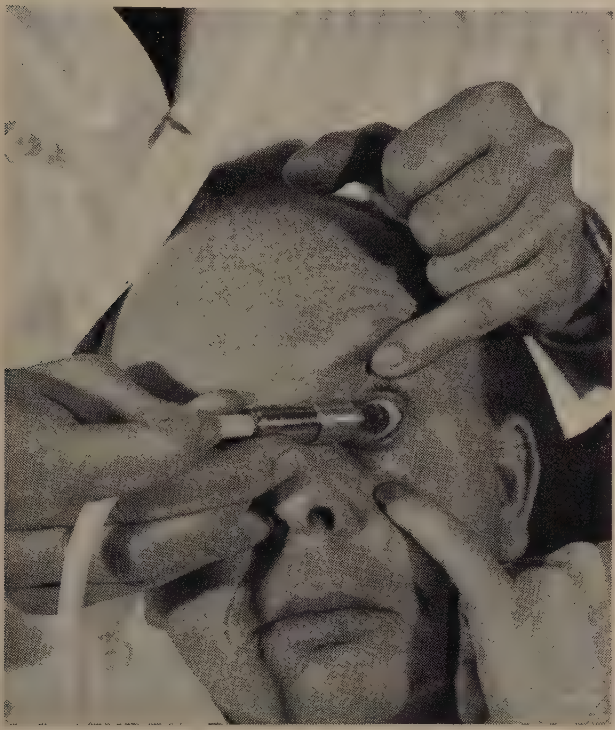

Fig. 13. Application of the KT tube for after-irradiation of a transplanted cornea. The tube is fitted, in this case, with a very small cone-shaped localiser, in order to restrict the beam of rays to the requisite small diameter. Since the depth penetration of the radiation is extremely small, special measures for protection against secondary radiation are not necessary. (The photograph was put at our disposal by Mr. P. J. L. Scholte, radio-therapeutist at the Municipal Hospital, the Hague.)

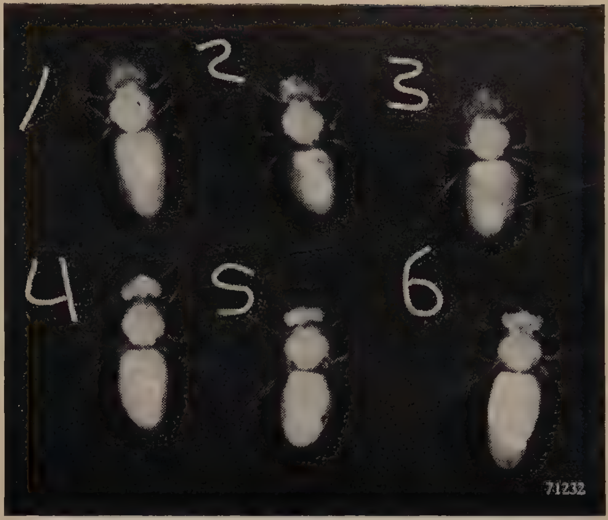

Fig. 15. X-ray photographs of honey bees after feeding them sugar water mixed with barium sulphate as contrast medium. Photographs 5, 3 and 2: half an hour after feeding with respectively 1%, 5% and 10% $BaSO_4$; photographs 1, 4 and 6 ditto an hour after feeding.

The intestines of the bee lie in its abdomen and consist chiefly of the pouch-shaped honey stomach, serving as temporary storage place for the food taken, the stomach or middle intestine, i.e. the digestive organ proper, and the rectum. The light spots seen on the photographs in the abdomen of each bee, are the honey stomach and the middle intestine. Their differences in size are due to differences in appetite; the honey stomach of bee no. 6, for example, is so well filled that its abdomen is considerably longer than that of the other bees. (The experienced beekeeper can see from the size of the abdomen if his bees collect much or little honey.) The organs of bee no. 2 are clearly shown in their normal position: the middle intestine lies in a loop. None of the six photographs shows positively the contrast medium in the rectum.

By means of photographs such as these, the absorption of the food by and its passage through the intestines of the honey bee could be studied. (The photographs were made in cooperation with Drs. A. J. de Groot, Lab. for Comparative Physiology, Utrecht, to whom we also owe this explanation.)

contact photographs of biological objects, so very thin that this could be done nearly — but still not quite — with light rays. *Fig. 14* gives as an example an X-ray photograph, made with a KT apparatus,

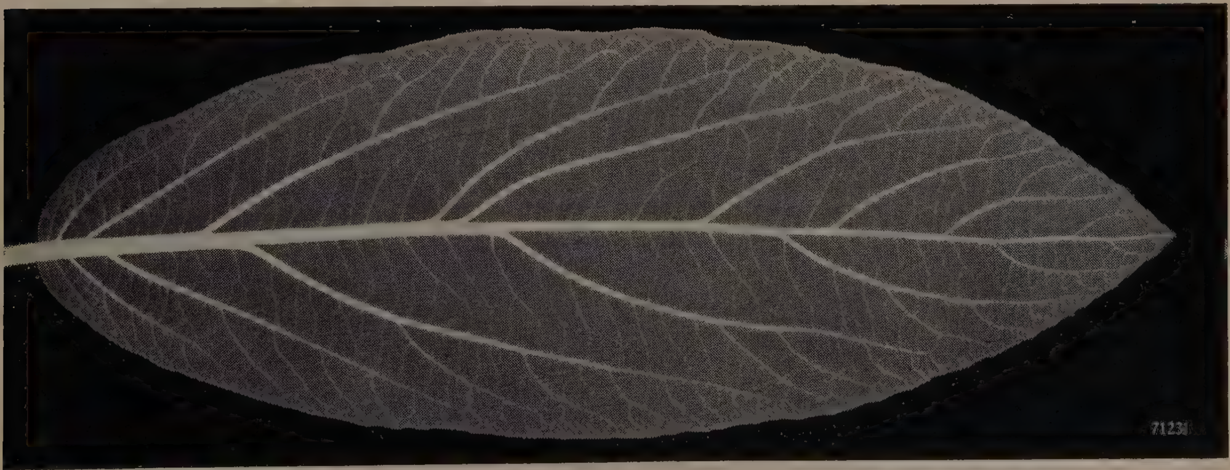

Fig. 14. X-ray photograph of a shrub-leaf, taken with the KT tube. In this case the voltage was 18 kV, the tube current 100 μA, the distance from focus to film 30 cm and the exposure time 180 sec.

of a relatively thick, barely translucent leaf of a shrub, *Fig. 15* is still more striking; it reproduces X-ray photographs of bees, after imbibing a sugar solution mixed with barium sulphate, the well-known contrast medium for radiological stomach examination; the six photographs correspond to different periods of time after feeding.

It may suffice to give these examples here.

Summary. The experimental X-ray tube described in this article (KT tube from the Dutch for smallest therapy, "kleinste therapie", tube) is 45 mm long and 14 mm in diameter, including the earthed metal jacket. The X-rays are excited in a very thin layer of gold, deposited on a beryllium plate, which at the same time serves as exit window for the rays. The tube can be loaded with a voltage of 25 kV and a power of maximum 2.5 W. The half-value thickness of the radiation is very small, viz. 0.5 mm tissue at 25 kV and 0.3 mm tissue at 10 kV, owing to the small "inherent filter" of the tube (equivalent to 1.5 mm beryllium). Very high dosage rates of some hundreds of thousands of röntgen units per minute can be obtained, in spite of the very small power, and a rapid decrease of the dose in proportion to depth, owing to the fact that the focus can be brought within 1 mm distance of the area to be irradiated. The dose distribution across the irradiated area is very uniform; due to the method of construction, the rays that pass the window obliquely are weakened more than axial rays, but this effect is more than compensated for by the natural directional effect of the continuous X-radiation, which is a consequence of its mechanism of origin, and is effective in the KT tube owing to the extreme thinness of the gold layer.

The X-ray tube is connected to the high-tension source by means of a flexible cable, 1.5 m long and 8 mm thick, with "Podur" insulation and earthed metal braiding. The high-tension generator is, in broad outline, identical with the well-known small 25 kV generator for projection television. A low short-circuit current and a relatively small output capacitance are essential to avoid overloading of the very small tube in the event of a fault (breakdown).

In contrast to the television generator, the generator of the KT apparatus is continuously adjustable for voltages up to 25 kV and currents up to 200 μA. The KT tube may be applied therapeutically for the removal of haemangiomae, the irradiation of the cornea after transplantation and the treatment of superficial tumors in the mouth and throat cavities. In addition, the tube can render good service in the testing of very light metals or very thin layers and for X-ray photographs of all sorts of biological objects; a series of radiographs of honey bees is, i.a., given as example.

SOME OF THE EFFECTS OF THE RELATIVE LENGTH OF DAY ON POINSETTIA AND POPULUS

by R. van der VEEN.

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Systematic tests have in certain instances successfully explained some of the complex processes of plant life which depend on the amount of light they receive. It has thus become possible to say that in Poinsettia a substance which normally promotes flowering, is inactivated by an inhibitor formed in the leaves when these are exposed to long days; this substance is carried upwards and downwards, the inhibitor only downwards. This hypothesis leads to an explanation to many apparently strange instances of flowering. Similar considerations apply to the winter dormancy of poplars.

Light is an essential factor in the life of a plant or, to express it more precisely, it controls a whole system of factors. Not only are the intensity and spectral composition of the light of influence; the length of the day, by which we mean the hours of daylight, is also highly important. A discussion of these effects has already appeared in this Review [1]).

Further investigation has shown that variations in the daily hours of light produce widely different effects; for example, in Poinsettia it is flowering, in the poplar the falling of the leaves that is so closely related to the relative length of the day.

In order to carry out experiments in this field it must be possible to vary the length of the "day" at will and to provide suitable reproducible conditions; we have accordingly made use of specially constructed greenhouses for this purpose [2]), in which plants are exposed exclusively to artificial light, and in addition are provided with an artificially controlled "climate".

The flowering response of Poinsettia

Poinsettia is decidedly a short-day plant, that is to say when it is exposed to less than 12 hours of light daily it will flower, whereas, if the duration of the illumination is more than 10 hours, one can be quite certain that it will bear no flowers. By varying the daily illumination, therefore, Poinsettia can be made flowering or vegetative at will.

When a plant which has developed during a long-day period (16 hours daylight) is given short-day treatment (9 hours light) for one week at a temperature of 26 °C and is subsequently restored to long days, it may be made to produce three similar laterals (*fig. 1*). The bud at the extremity is then a flower primordium which is, however, incapable of development. Just below this bud there will be three side shoots, which, having grown during the long days, remain vegetative. (This is the only way in which equivalent laterals can be obtained; by removing the tops, new laterals can be produced, but, as a rule, the upper ones will develop more strongly than the lower.)

Fig. 1. By growing Poinsettia under long days (16 hours), then reducing the daily light to 9 hours for one week and finally restoring the plant to the 16-hours treatment, the three equivalent laterals (*1*, *2* and *3*) shown in the illustration are obtained.

[1]) R. van der Veen, Philips techn. Review **11**, 43-49, 1949.
[2]) R. van der Veen, Philips techn. Review, **12**, 1-5, 1950 (No. 1).

Fig. 2. Poinsettia after 10 "short" days. The inflorescence comprises but few flowers and lacks the halo of red foliage normally present when the plant is in full bloom.

To ensure fully developed flowers the plant must be given at least ten short days in succession, although in that case the cluster of red leaves round the inflorescence, so characteristic of Poinsettia, is lacking; the display is scattered, with only a few flowers (*fig. 2*). After a larger number of short days more flowers are formed, but they are still rather wide apart and the inflorescence is green. After a treatment of about 30 short days there is suddenly a marked change; the inflorescence is then more concentrated and the red leaves appear (*fig. 3*). The plant thus requires some 30 short days for the induction of a complete inflorescence.

As Poinsettia shows suc a pronouncedh response to the daily duration of the illumination, this plant was selected for the following tests.

A plant, exposed for one week to short days, produced an array of three similar laterals, one of which was removed. Of the two others one was exposed to long days (16 hours daily) and the other, by covering it for a number of hours, to short days (9 hours). As was expected, these two laterals responded independently; the short-day lateral produced flowers, whereas the other remained vegetative (*fig. 4*). The latter could nevertheless be made to flower by removing all the leaves (*fig. 5*), doubtless owing to the influence of the leaves on the short-day branch. This test shows that — as had been demonstrated already [3]) — the response to the relative length of the day takes place not in the growth-centre, but in the green leaves.

One single leaf left on the long-day branch was enough to prevent it from flowering. Nor were any flowers obtained on a plant, raised under long-day conditions, from which all the leaves were removed. When a plant from which the leaves have been removed is subjected to short-day treatment, the flowers again fail to appear; hence removal of the leaves is not in itself sufficient to promote flowering.

This result can be explained by assuming that under short-day conditions a flower-inducing substance is produced in the leaves, which is transported through the stem both upwards and downwards; when this substance passes a leaf which is exposed to long days it is rendered inactive by another substance formed in this leaf.

The following test confirms this assumption. A plant was taken having two laterals of the type

Fig. 3. After about 30 short days Poinsettia comes rather suddenly into full bloom; the inflorescence is compact, with a circle of red leaves round the blooms.

[3]) See, e.g. W. S. Garner and H. A. Allard, Localisation of the response of plants to relative length of day and night J. Agric. Res. **31**, 871-920, 1925.

Fig. 4. Poinsettia of which the left-hand lateral has been exposed to short days (9 hours) and the right-hand one to long days (16 hours). The first is in bloom, the second purely vegetative.

Fig. 5. After removal of the leaves from the right-hand lateral in fig. 4, this also flowers under long-day conditions, owing to the influence of the left-hand lateral, which is still receiving short-day treatment.

depicted in *fig. 6*. Lateral *A* received short-day treatment, the rest long days of light. Flowers thus appeared on *A* (fig. 6*a*), but none on *C* and *D*. The leaves were then removed from *B* and *D*, but not from *C* (fig. 6*b*), for the purpose of ascertaining whether *D* would then bear flowers. Even after three months, no flowers appeared. Although en route from *A* to the growth centre of *D* not one leaf is passed which was exposed to the long-day treatment, the assumed flower-inducing substance was nevertheless inactivated on its way from *A* to *D*.

Evidently, the reason why the flowers are prevented from being formed is to be found in a substance produced in the leaves on *C* and carried downwards by way of *B*. In *B*, this substance neutralises the flower-inducing element coming from the leaves of *A*. By removing all the leaves from *C* as well, it should therefore be possible to check this neutralising effect and, actually, within one month from the time of stripping lateral *C*, buds were clearly visible not only on the extremity of *C*, but also on *D* (fig. 6*c*), notwithstanding the fact that *B*, *C* and *D* were still being exposed to long days.

It may be deduced from experiments that the flowering of Poinsettia is governed by the interaction of two substances of which the one induces flowering whilst the other renders the first inactive. It is known that auxin, the growth hormone, also tends to check flowering, and the obvious inference is that the inhibitor produced in the leaves as a

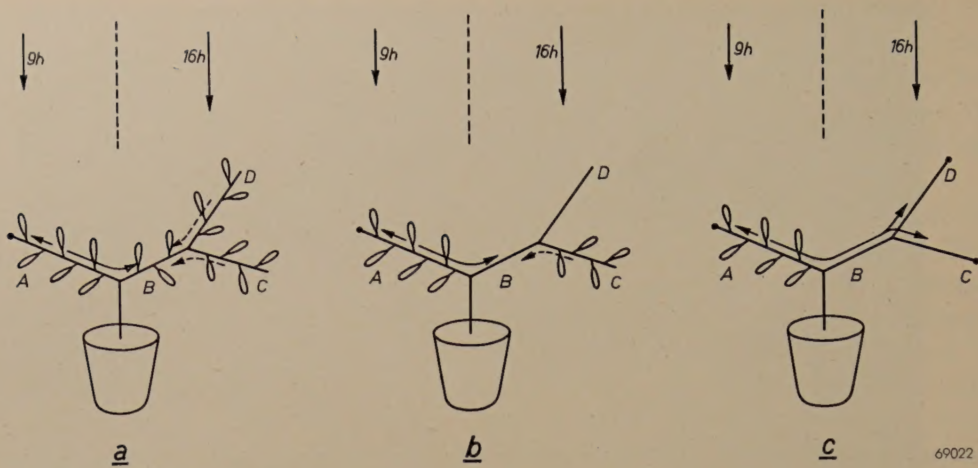

Fig. 6. Leave-stripping tests with Poinsettia. Lateral *A* is exposed to short daily illumination (9 hours), *B*, *C* and *D* to long days (16 hours).
a) All branches vegetative; only *A* flowers.
b) *B* and *D* stripped of leaves; *D* does not flowers.
c) When *C* is stripped as well, flower buds appear on *D* and *C*.
The full-line arrows indicate the movement of the flower-inducing substance formed in the leaves of the short-day lateral (*A*); the dotted arrows show the transport of the neutralising agent produced in those leaves which are exposed to long days.

result of long-day treatment is an auxin. This has not been proved, however. At the same time, it is certain that a low auxin level is not in itself sufficient to promote flowering; a positive factor is essential, namely the flower-inducing substance which is produced in the leaves during the short-day treatment.

Dormancy of Populus

In the same way that Poinsettia is a plant sensitive to the length of day from the aspect of flowering, the poplar shows a similar response as regards its dormancy. It is only when the days are short that the leaves are shed; during the longer days growth continues. A comprehensive study of the subject has already been published [4]) and we shall content ourselves with a summary of this work.

The poplar comes into growth in the spring in

[4]) R. van der Veen, Influence of daylength on the dormancy of some species of the genus Populus, Physiologia Plantarum 4, 35-40, 1951 (No. 1).

Fig. 7. Two specimens of poplar (Populus robusta). Left: exposed to short days (12 hours) for 2 months. Right: exposed to long days (16 hours) for 2 months. The short-day plant has stopped growth. (Note the resting buds at the end of the twigs.) The growth of the long-day plant is in no way retarded.

consequence of the rise in temperature; the length of the day does not affect it. When the tree is exposed to short days, dormant buds are formed at the ends of the twigs within 6 weeks and all growth is arrested. In long days, however, the tree continues to grow (*fig. 7*).

If trees exposed to short-day treatment are examined four months after budding, all the leaves are found to have been shed, the tree being then quite dormant. This takes place independently of temperature; it is therefore solely due to the shortening of the days that the poplar becomes dormant (*fig. 8*). Plane trees respond in the same way (see *fig. 9*).

The first question is now in how far the branches of one and the same tree respond independently to the light conditions. To investigate this, a first-year specimen of Populus robusta was pruned down to two comparable branches, of which one was exposed to long days (16 hours) and the other to the short-day treatment (9 hours). In five weeks it was apparent that the short-day branch was becoming dormant, whilst the other was still growing. After three

Fig. 8. The same examples as in fig. 7, three months later under the same conditions. Although not exposed to cold, the short-day specimen (left hand) is fully dormant. The other continues to grow.

months of this treatment the last-mentioned branch still showed pronounced development, being much thicker and heavier than the other now dormant one.

This test was repeated with other specimens, with the same result. It may therefore be assumed that each branch of the poplar, too, responds independently to the lighting conditions. Fig. 9 illustrates this in the case of a plane tree.

We have made some experiments by stripping the leaves from poplars in the same way as we did with Poinsettia.

1) One branch exposed to short days was dormant in five to six weeks. As soon as the terminal bud was formed and dormancy was clearly evident, the leaves were removed; the dormant condition then quickly ceased and the terminal bud began to develop. In another case, where stripping of the leaves was delayed for four weeks after the onset of dormancy, the terminal bud showed no change and the tree remained dormant for another month.

Something very similar happens when a poplar, which shows the first signs of dormancy after short-day treatment, is exposed to long days; when this is done, the terminal buds soon resume their growth. On the other hand, once the tree has been dormant for a longer time, long days are ineffective.

2) We have seen that in Poinsettia the capacity of a short-day branch to flower can be transmitted to a long-day branch stripped of its leaves. The question is now whether from the aspect of dormancy there is a similar transmission from one branch to another in the poplar.

In order to answer this we subjected one branch of a poplar plant to the short-day treatment, at the same time stripping the leaves from the second branch. No influence of the short-day branch, however, could be observed, even after some months.

The results of these tests may be interpreted in the following manner.

Growth-promoting hormones (auxins) are formed in plants just below the growth centre and usually also in the leaves. They increase the development of the growing shoots, but they inhibit the bursting of the buds. It is well known that auxins are transported particularly in a downward direction.

The reason why the axillary buds of a normally growing branch do not burst is to be found in this auxin effect; the descending auxin inhibits the bursting of the buds. If the top of the branch is removed, however, the lack of this source of auxin considerably reduces the concentration of auxin in the region of the upper axillary buds. The inhibiting effect is thus absent and these buds will start growing, as occurs in nature when the end of a branch is cut off.

During long-day periods the production of auxin is in equilibrium with the consumption (by oxidation) of this substance, so that a certain concentration is maintained.

When the days shorten it appears that another substance is formed in the leaves which also checks the bursting of the buds, but in addition causes the vegetative centre to change into a dormant terminal bud. This inhibitor is, therefore, definitely transported upwards. As soon as the growth of the branch comes to an end, the flow from the auxin source just below the head ceases automatically.

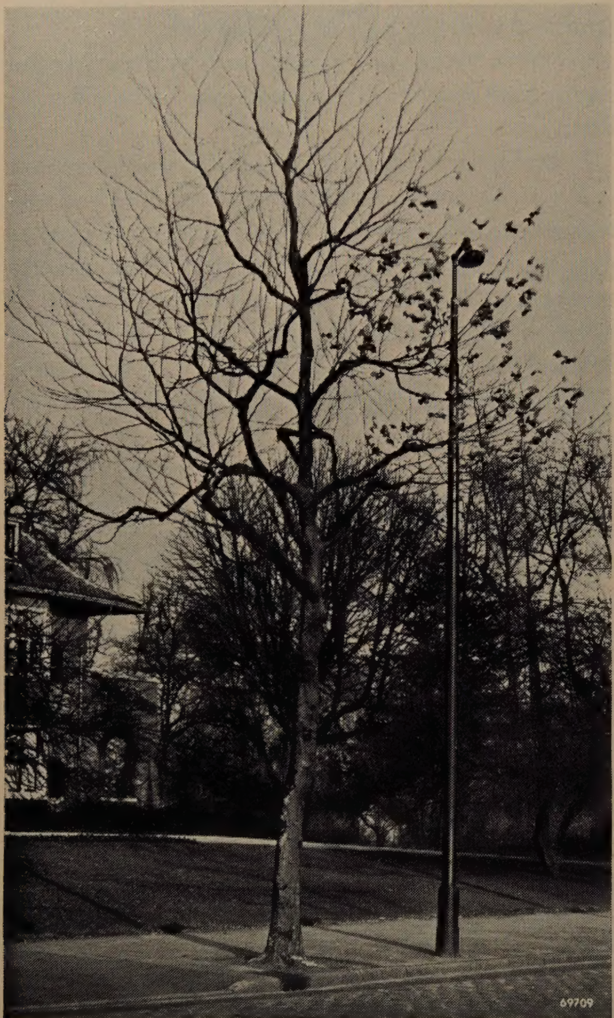

Fig. 9. Photograph of a plane tree taken at the end of November at Eindhoven. All the leaves have been shed except for that part which, owing to its proximity to the street lamp, has had the benefit of "long days".

This inhibitor, which induces the winter dormancy, is stored in the buds. It does not disappear as quickly as the auxin; hence the time necessary, possibly months, before the dormant branch will again become green. Everyone knows that branches of the chestnut placed in a warm room in November will not sprout, but that branches picked in February will immediately burst into leaf.

At the onset of dormancy the surplus of inhibitor in the poplar is so small that — if this substance is no longer being produced owing to the length of the day or to stripping of the leaves — the concentration quickly drops below a certain minimum, the buds begin to grow and in the growing branch the auxins gain the supremacy.

Dormancy of longer duration results in the production of more and more of the inhibitor, so that it becomes increasingly difficult, or even impossible, to activate the buds by long days or by stripping. It is only after spontaneous leaf shedding, followed by the necessary period of rest, that the poplar is again so conditioned that the buds will open either in long or short days, the temperature being sufficiently high. During the winter dormancy the buds are particularly resistant to cold.

For the most part these considerations are not new. Murneek and others [5]) have already published a comprehensive survey on the photoperiodism of plants, and Wareing [6]) has given a survey of the literature of the effect of day-length on trees. The tests described above serve as good illustrations of both, having been carried out on plants which have been found to lend themselves particularly well for the purpose.

Summary. Poinsettia and Populus are plants which show a pronounced reaction to relative lengths of daylight and which are well adapted for tests in this direction. In both cases it is found that different branches of a given specimen respond quite independently to the length of the day and that "perception" of the length of day takes place in the leaves.

By subjecting one part of a Poinsettia to relatively short days and another to relatively long ones, and by stripping the leaves from some of the branches of the last-mentioned section, results are obtained which lend support to the following hypothesis. In those leaves which receive short daily illumination a flower-promoting substance is produced which is transported both upwards and downwards in the plant; in those leaves which receive long daily illumination an antagonistic substance or inhibitor is formed which is transported downwards only. When this latter substance encounters the flower-inducing substance, the latter is rendered inactive and those parts of the plant above the meeting point will not be influenced by the flower-inducing substance. Flowers do appear, however, at those point where the flower-inducing agent is able to penetrate without meeting the inhibitor.

In poplars, bursting of the buds is dependent on the temperature, whereas the onset of dormancy is purely a question of the duration of the daily illumination received. After five to six weeks of short days the terminal buds have been formed and the tree is dormant. The results of experiments with day-length variation and stripping of the leaves of Populus robusta may be interpreted as follows. In long days a certain concentration of auxin is maintained, this is transported downwards only; in short days an inhibitor is formed in the leaves which moves both upwards and downwards. This inhibitor accumulates at the buds and is inactivated very slowly.

The experiments described were carried out entirely in artificial light, under reproducible, artificial climatic conditions.

[5]) A. E. Murneek, R. O. Whyte et al., Vernalization and photoperiodism, Waltham (Mass.) 1948.

[6]) P. F. Wareing, Photoperiodism in woody species, Forestry 22, 211-220, 1947.